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THE BEHAVIOR OF THUNDERSTORMS OVER ALBERTA FORESTS

BY

© RICHARD G. LAWFORD

A THESIS

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "The Behavior of Thunderstorms over Alberta Forests" submitted by Richard G. Lawford in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

This is a study of thunderstorms reported by lookout observers of the Alberta Forest Service during the period 1962 to 1968 inclusive. From the study has come information on the spatial and temporal distribution of thunderstorms, on the characteristics of clouds that produce these storms and on the lightning strikes that are the result of them.

The spatial distribution of thunderstorms and thunderstorm characteristics indicate that there are preferred areas of storm development associated with geographical features such as the Clear Hills and the foothills of the Rocky Mountains. In general thunderstorms occur in the afternoon although nocturnal storms form in the lee of the Continental Divide and the northeastern part of the province. Afternoon air mass storms appear to develop over hills and other sources of low level heating. The differential heating occurring over slopes of different aspect gives rise to thermals over the southern slopes. These thermals modify the atmosphere and lead to durable, well-organized, active thunderstorms.

The development of thunderclouds over mountainous terrain continues late into the season. Evidence is presented to suggest that a meso-scale wave phenomenon accentuates the organization and growth of cumulonimbus clouds in the lee of the Continental Divide. Over rugged terrain short-duration thunderstorms discharge rapidly. Storms in the lee of the Rocky Mountains frequently produce cloud-to-ground discharges without producing precipitation. These results are explained in terms of the intensification of the potential gradient which occurs when a cloud approaches a mountain.

An examination of the relationships between hailstorms and thunderstorms which showed that hail was more likely from storms occurring over higher terrain in the lee of the Continental Divide lent support to the conclusion that topographic and orographic effects partially determine the behavior of thunderstorms in Alberta.

ACKNOWLEDGEMENTS

The results presented in this thesis must be accompanied by a tribute to those many individuals who have cooperated in making it a reality. The data were, in the main, supplied by Alberta Forest Service personnel. Conversations with Mr. J. W. McLean and other foresters have been responsible for stimulating the ideas presented in this dissertation which link the fields of forestry and meteorology.

Without the facilities of the University of Alberta Department of Computing Science and their computer the analysis of these data would have been impossible. The Meteorological Branch of the Department of Transport are gratefully acknowledged for the financial backing they supplied.

The valuable comments of Professor Richmond W. Longley have not only served to solidify some of the ideas presented in this report, but they have assisted in modifying the presentation of these ideas. Dr. E. R. Reinelt is also thanked for adding his comments and thereby increasing the precision of the language employed.

Conversations with other students, such as Mr. J. Pakiam of the Saskatchewan Research Council, and faculty, such as Dr. K. Hage of the University of Alberta, regarding topics related to both thunderstorms and the efficient use of the computer have resulted in resolving technical difficulties and stimulating different approaches to the problems of thunderstorms.

The typing of this final draft was competently completed by Mr. R. P. Weatherburn. Mr. D. Ferguson and Mr. R. P. Weatherburn are duly thanked for their assistance with maps and graphs.

The continual encouragement of my wife, Barbara, throughout the duration of this research has generated the motivation necessary to release any potentials manifested in this thesis.

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CHAPTER I

THE PROBLEM DEFINED

Hast thou entered into the treasures of the snow? or hast thou seen the treasures of the hail? (Job 38:26)

1.1 INTRODUCTION

Man's interest in the weather, as the above quotation from Job demonstrates, has existed for many millennia. This is not surprising, for, independent of man's location or man's generation, meteorological phenomena have always constituted a major controlling factor in his environment.

Today's meteorologists are capable of predicting changes in the weather with a high degree of accuracy if these changes are the products of slow, synoptic-scale processes in the atmosphere. They have not realized this success in predicting highly localized phenomena, such as the thunderstorm, which evolve from rapid, mesoscale processes. Because these short-lived, intense storms can do extensive damage to property (through the lightning, hail, high winds and intense rainfalls associated with them), any improvement in the ability to predict them accurately in time and space would be of assistance to all users of thunderstorm forecasts.

The most destructive meteorological events in the province of Alberta are those associated with intense cumulonimbus activity.

Douglas and Hitschfeld (1958) point out that hail losses to agriculture, averaged over a few years prior to their report, cost 20 million dollars annually. Lightning produces 45 per cent of the forest fires which destroy 3.7 millions of dollars worth of timber each year. Thunderstorms are also responsible for countless inconveniences to people on holiday, blackouts of hydro and telephone networks, as well as fire, wind and hail damage done to personal property.

Lightning-caused forest fires have for years been the concern of Alberta Forest Service personnel. Many of Alberta's cumulonimbus clouds are electrically active storms capable of initiating forest fires by cloud-to-ground lightning. Although such fires may have humble beginnings, under the proper fuel conditions they can, if unchecked, develop in a day into a devastating inferno. To the conservation-minded forester, detection and suppression of fires are of prime concern. Because this task reduces to minimizing the time lags between the inception and detection of the fire and the deployment of men and equipment into the threatened area, strategic positioning of search aircraft, personnel, and fire-fighting equipment is desirable before the fire commences if possible. A forecast delineating areas where thunderstorms are probable and fuels are dry, would provide the protection officer with an objective basis for making his decisions. Because scientific decisions require accurate thunderstorm forecasts, Alberta Forest Service personnel encouraged this research into the problem.

In this chapter, lightning-caused fires are reviewed in terms of their times of occurrence and the extent of the damage they do to Alberta's timber. A project is then proposed which could provide a partial solution to the forecast problem lightning storms represent.

This chapter concludes by articulating the objectives of this present study. The reader is referred to Appendix B for a description of any technical non-meteorological terminology which may occur in this or subsequent chapters. Fire reports between 1961 and 1968 inclusive were used to complete the analysis.

1.2 TEMPORAL CHARACTERISTICS OF LIGHTNING CAUSED FOREST FIRES

Figure 1.1 displays the yearly variations in the number of forest fires in Alberta forests. The results in Table 1.1 indicate there has been a decrease in the relative frequency of lightning-caused fires. Although the expansion of oil, and pulp and paper industries in the forested areas may be causing this decrease, disruption

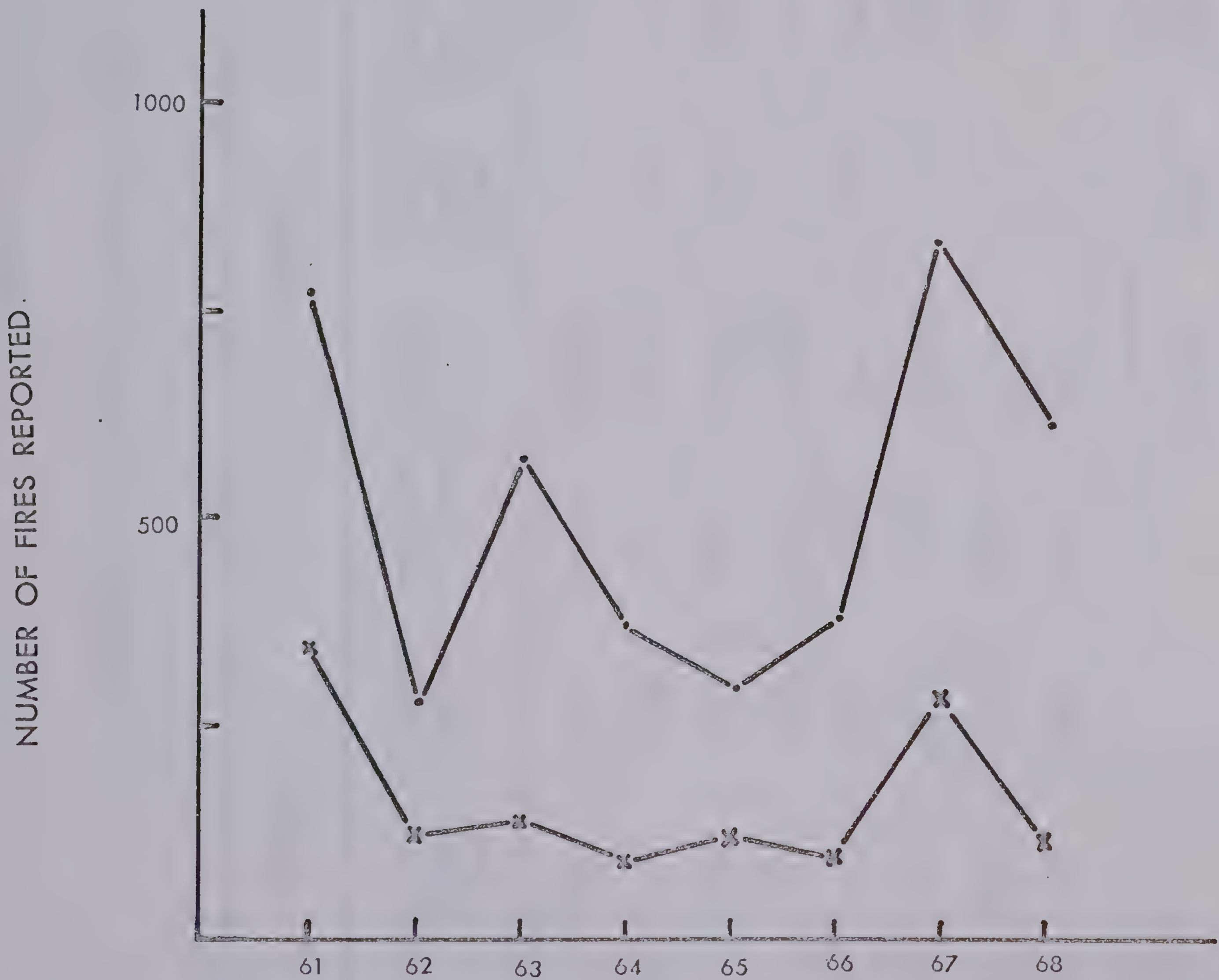


Figure 1.1 YEARLY VARIATIONS IN THE FREQUENCY OF FOREST FIRES. The frequency of all forest fires are represented by dots while crosses represent the frequency of lightning-caused forest fires.

TABLE 1.1

TEMPORAL VARIATIONS OF LIGHTNING-CAUSED FOREST FIRES

ANNUAL				SEASONAL			DAILY		
Year	Freq. Light. Fires	Total Fires	Per cent of total	Month	Freq. Light. Fires	Relative Freq. (per cent)	Time Internal	Freq. Light. Fires	Relative Freq. (per cent)
1961	357	789	45.4	April	7	0.6	0000-0259	27	2.1
1962	125	283	44.2	May	125	8.4	0300-0559	20	1.4
1963	282	571	49.2	June	541	36.1	0600-0859	50	3.3
1964	94	370	25.4	July	531	35.4	0900-1159	72	4.9
1965	124	282	44.0	Aug	242	16.2	1200-1459	326	21.7
1966	108	387	27.9	Sept	32	2.2	1500-1759	414	27.5
1967	297	832	35.8	Oct	6	0.5	1800-2059	268	17.9
1968	116	598	19.4	Nov	2	0.2	2100-2359	100	6.6
				Unknown	9	0.4	Unknown	218	14.6
				TOTAL	1495	100.0	TOTAL	1495	100.0

of this trend in 1965 suggests the decrease is primarily the result of chance factors.

Fires of all types were frequent during 1961, 63 and 67. The precipitation deficits tabulated in Table 1.2 indicate that throughout Alberta dry conditions prevailed. This suggests that both forest fires in general and lightning-caused forest fires are most frequent during years with normal or below normal rainfall. On the surface this observation appears rather paradoxical. It suggests that convective activity (the process responsible for most of Alberta's liquid precipitation) is at a minimum during years when lightning-caused fires are most prevalent.

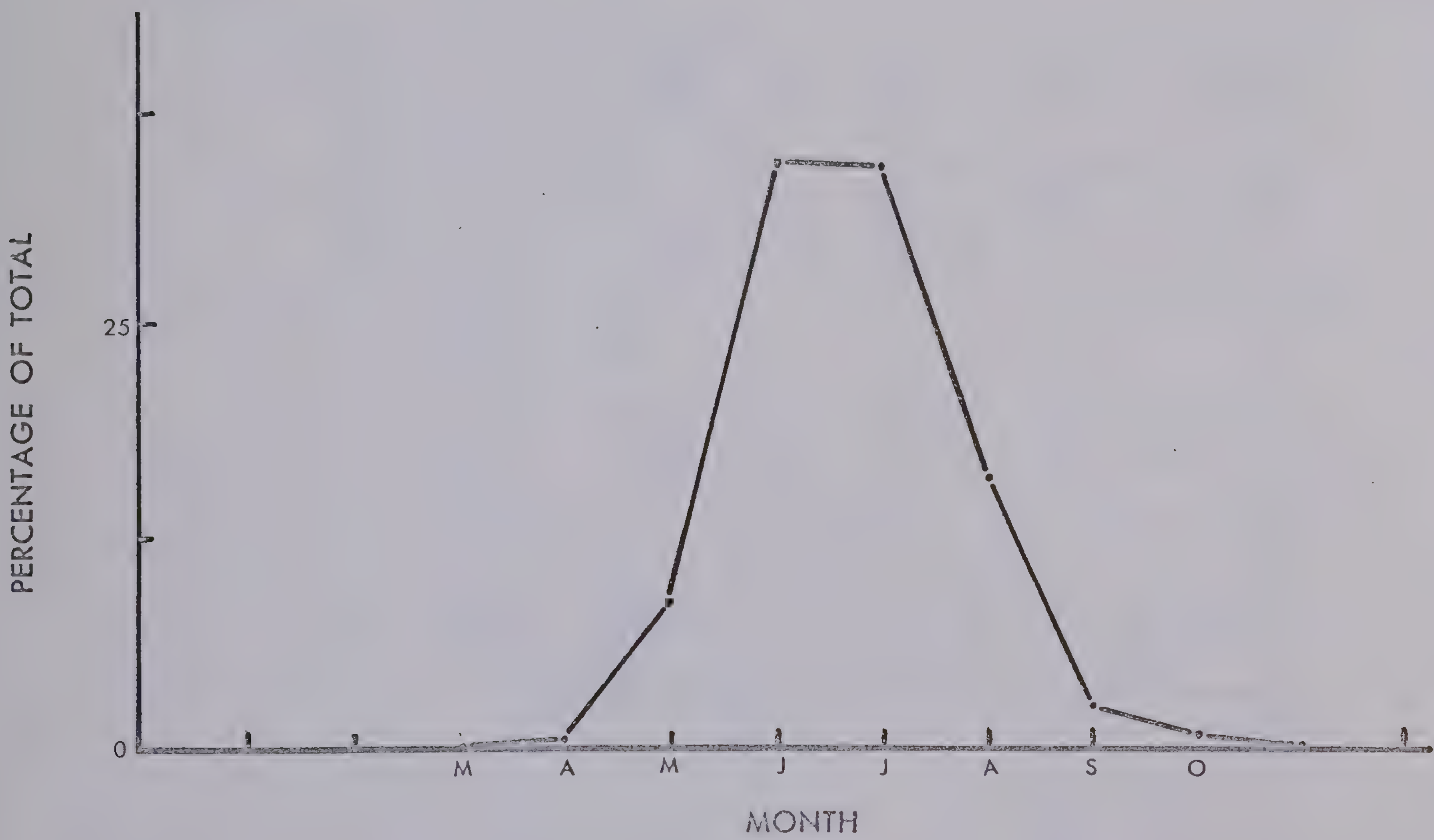


Figure 1.2 THE SEASONAL DISTRIBUTION OF FIRES BY MONTH. A plot of the per cent relative frequency of fires resulting from lightning strikes versus the month.

TABLE 1.2

PRECIPITATION DEFICITS FOR YEARS OF HIGH FIRE INCIDENCE

STATION	NORMAL RAIN (IN.)	1961		1963		1967	
		RAIN (IN.)	DEFICITS (IN.)	RAIN (IN.)	DEFICITS (IN.)	RAIN (IN.)	DEFICITS (IN.)
CALGARY	11.6	10.1	-1.5	12.4	+0.8	5.3	-6.3
EDMONTON	13.2	8.3	-4.9	9.2	-4.0	10.1	-3.1
EDSON	15.0	17.7	+2.7	11.9	-3.1	10.2	-4.8
FORT MCMURRAY	11.9	9.7	-2.2	9.5	-2.4	12.8	+0.9
GRANDE PRAIRIE	10.9	14.0	+3.1	7.1	-3.8	5.4	-5.5
WHITECOURT	15.0	17.8	+2.8	12.6	-2.4	6.7	-8.3

This situation results from the dry fuel conditions present in environments conducive to fire development. It is concluded that without proper fuel conditions it is improbable that even a large number of thunderstorms would result in a forest fire for any area.

Figure 1.2 presents the percentage relative frequency of lightning-caused fires using a monthly time base. Lightning fires become significant during the month of May, reaching a maximum of 37 per cent of the mean annual total during June. Fires originating from lightning persist through July and then their occurrence decreases to 2 per cent for September. This seasonal distribution of fires suggests that either:

a) thunderstorms and lightning strikes are most frequent during the months of June and July; or

b) thunderstorms occurring during June and July are most effective in initiating fires; or

c) both.

The diurnal variation of fires initiated by lightning is displayed in Figure 1.3. It should be noted that 15 per cent of the fires commenced at unknown times. It is probable that most of these fires occurred in sparsely surveyed forests in the northern part of the province or at night when lookout operators were sleeping.

The relative frequency of fires caused by lightning reaches a diurnal maximum between 1500 and 1600 MST, coinciding with the time of maximum thunderstorm activity. Two secondary maxima appear, one between 1800 and 1900 MST and the other between 2300 and 2400, suggesting storm activity revives at these times in some parts of the province.

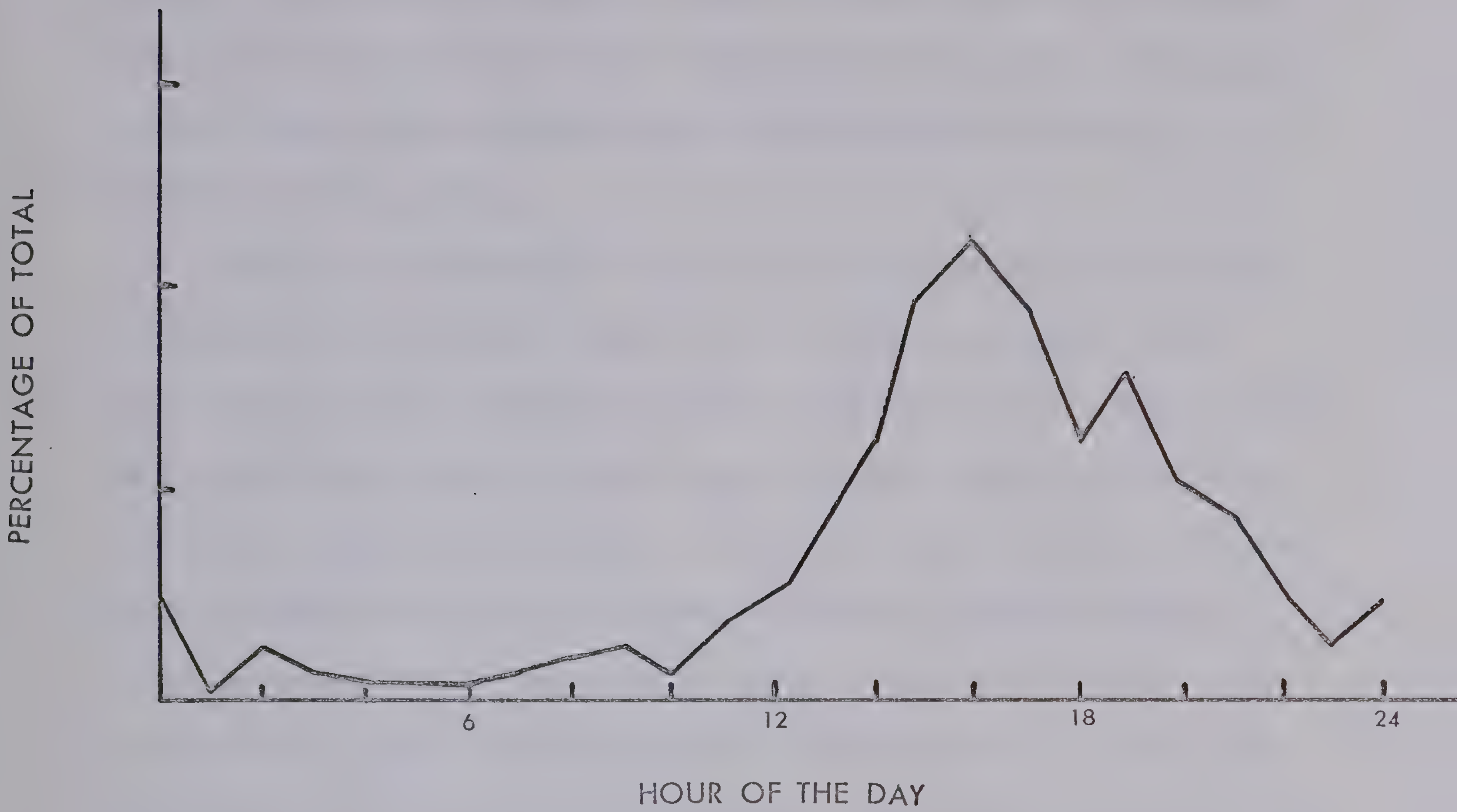


Figure 1.3 DIURNAL VARIATION OF FIRES FROM LIGHTNING. The percentage relative frequency of fires resulting from lightning strikes by hour of the day.

1.3 OTHER CHARACTERISTICS OF FIRES INITIATED BY LIGHTNING

The following analysis of fire reports obtained from the Alberta Forest Service areas of responsibility for an eight-year interval commencing in the spring of 1962 is included at this juncture. A more complete documentation of lightning-caused forest fires is found in Appendix A.

Lookout operators reported 60 per cent of the 1420 fires initiated by lightning. Alberta Forest Service aircraft searching for the smoke plumes rising from fires existing in areas recently traversed

by thunderstorms discovered 18 per cent of the lightning-caused fires. Pilots of other aircraft reported another 10 per cent. As the lookout network and the aerial patrol were responsible for spotting 86 per cent of these fires we must conclude that both methods are useful in detecting lightning fires.

When first detected, 56 per cent of these fires are confined to an area of 0.25 acres or less. If a fire is not spotted in its early stages it will grow to encompass a much larger area. The 98 fires which covered more than 100 acres prior to their detection testify to this fact. Fifty-four per cent of these large fires exceeded 500 acres prior to their detection. The average time which elapses between a lightning-caused fire's inception and detection exceeds 34 hours. The large time lags associated with dry fuel conditions are generally responsible for the fires which have become large prior to their discovery.

Over the eight-year interval, 288,000 acres of timber were gutted by lightning-caused fires, each fire averaging 205 acres. The fact that fires which had expanded to 500 acres prior to their detection destroyed 94 per cent of the timber lost, 5100 acres per fire, emphasizes the disastrous effects of inadequate detection. Fires which had spread to between 100 and 500 acres before being detected destroyed in the mean 218 acres before being extinguished. The fact that fires larger than 100 acres upon detection are responsible for 97 per cent of the total fire damage caused by lightning underlines the need for a scientific basis for fire detection planning, a basis which is founded on both the climatic vicissitudes of cumulonimbus as well as accurate thunderstorm forecasts.

Lightning-caused fires are most common on level or rolling terrain. Only 6 per cent of the fires for which physiographical documentation was given occurred in mountainous terrain. Although the distribution of fires relative to orography partially reflects the proportionate areas of forest growing on mountainous terrain, it also suggests that lightning, like hail (Powell, 1961) is most frequent over gently sloping terrain.

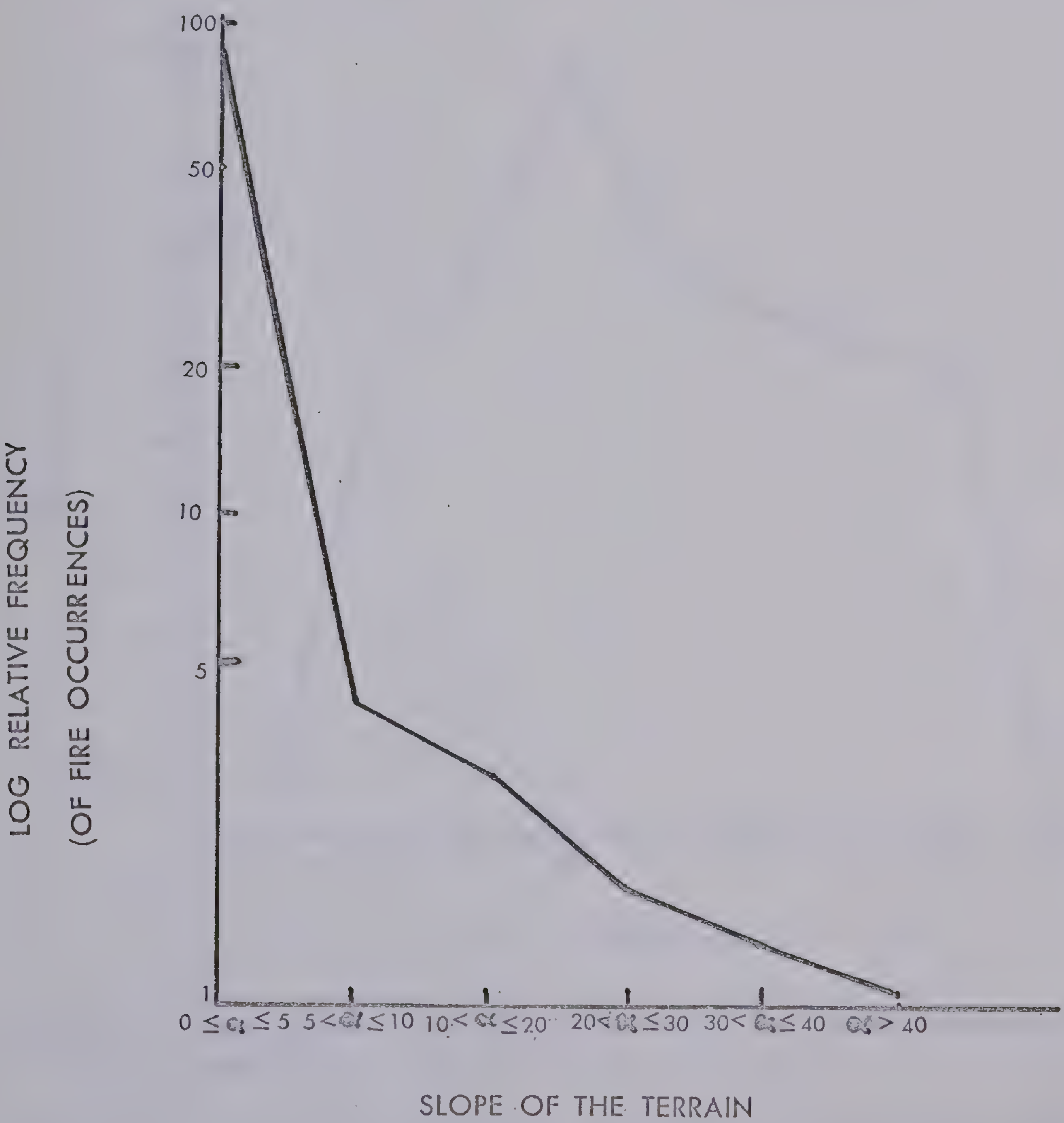


Figure 1.4 THE RELATIVE FREQUENCY OF LIGHTNING-CAUSED FIRES RELATED TO THE SLOPE OF THE TERRAIN (α).

Figure 1.4, which is a plot of the log of the relative frequency of fire occurrence against α (the slope of the terrain) indicates that most fires commence in localities where the slope is less than five degrees.

Figure 1.5 is also of interest. It is a plot of the number of fires which occurred versus the aspect of the slope upon which the fire did occur.

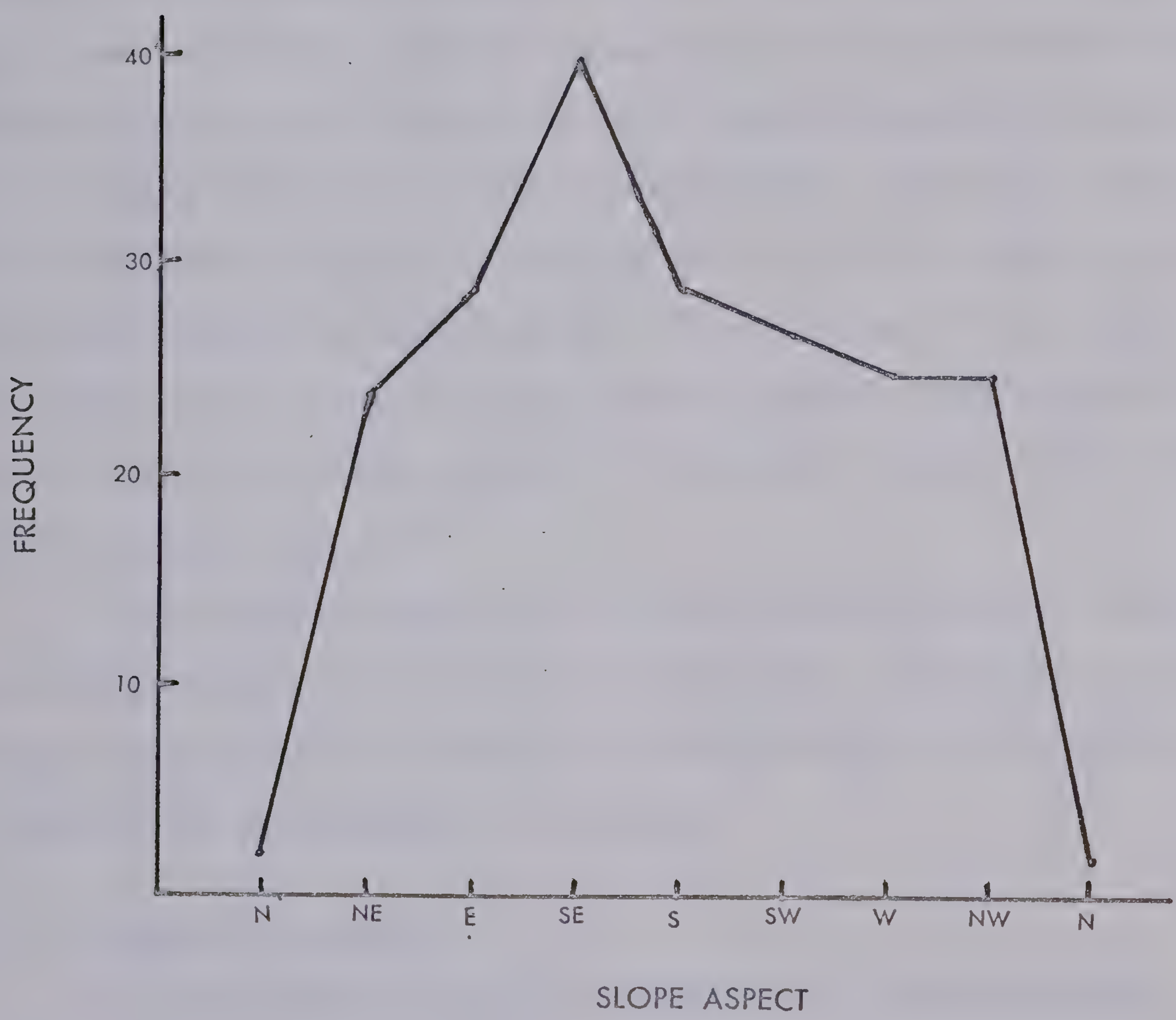


Figure 1.5 THE FREQUENCY OF LIGHTNING-CAUSED FIRES AGAINST SLOPE ASPECT.

This graph shows that lightning-caused fires tend to occur on the southern and eastern slopes of hills which suggests that the activity of a thunderstorm may be linked to the aspect of the slope.

From the detailed reports which contained information regarding the predominant characteristics of fire behavior at the time when action against the fire was initiated, it was found that 53 per cent of the fires were surface fires, i.e. fires which travel primarily along the ground, igniting trees from below, while only 9 per cent of the fires were crown fires which spread by jumping from tree-top to tree-top. The other 38 per cent were ground fires. Most lightning-caused fires move slowly during their initial stages of development. Only 12 per cent of the fires spread at speeds greater than 600 feet per hour while 55 per cent were expanding at rates less than 2 feet per hour. Forty-six per cent of the fires started in spruce stands, suggesting that strikes in spruce stands may be more effective in initiating fires than strikes in pine or deciduous stands.

The foregoing statistics have demonstrated the need for research into the problems of lightning-caused forest fires. A proposal called Project Metlite is now discussed as a possible solution to the problem of forecasting the occurrence of lightning.

1.4 A POTENTIAL SOLUTION

As the preceding analysis has demonstrated, lightning-caused forest fires show definite affinities for certain onset times and locations. Because these fires, with one or two exceptions, are associated with thunderstorms it follows that cumulonimbus clouds will exhibit similar preferences for time and place of development. An evaluation

of the temporal and spatial characteristics of Alberta thunderstorms would not only increase the understanding of the interactions between topography and convectional storms and provide important input into future thunderstorm models but it could provide a scientific basis for the administration of operations affected by lightning and hail as well as assisting in the evaluation of a more accurate forecasting technique.

A long-term solution to the labyrinthine problem of accurately forecasting storm development is outlined below. Because four or five years of work would be required to complete the details of the analysis scheme displayed in Figure 1.6, the research reported on in this paper limits itself to providing solutions of intermediate objectives. A possible solution, dubbed Project Metlite, is discussed in detail in Project Metlite, 1969 Field Program (Lawford, 1970). The final result, a computer program designed to delineate areas of both probable convective activity and possible fire occurrence, will be based on models developed at intermediate stages of analysis. The background analysis will consist of a meso-scale climatic analysis of the influences of the underlying terrain as it influences thunderstorm characteristics.

The relationships between the rate and extent of storm development, inasmuch as it is affected by the vertical and quasi-horizontal gradients of temperature, moisture, and wind, will be studied to derive the necessary and sufficient conditions for thunderstorm development. Various statistical techniques (e.g. multiple discriminant analysis) will provide models relating the probability of storm development to the controlling features of the synoptic situation. Combining the results from the study of the climatology of the low levels with the potential of the overlying free atmosphere to initiate and propagate

thunderstorms, an index defining the probability of storm development for any specific location could be derived.

The dynamics of developing thunderstorms can be studied by using visual lightning and cloud observations, radar observations, and surface weather observations. A knowledge of the vertical and lateral dimensions of the storm coupled with cloud-to-ground lightning counts during various stages of the storm's development (derived from radar observations and visual observations of glaciation within, and precipitation from the base of, the cloud) could lead to a pseudo-physical cloud model. This model might not only explain the gross features of an active thunderstorm but it could provide an empirical estimate of the probability of lightning from a storm of known dimensions. Coupling information about the distributions of temperature, moisture and wind fields and the anticipated cloud development with this model would provide an objective, reliable basis for a probability forecast of lightning occurrences.

The type of information of greatest value to the protection forecaster must be kept in mind when designing an experiment, as his interest in the lightning-caused fires provided initial impetus to the research. A probability forecast would be the format of the final forecast because it gives a quantitative evaluation of the likelihood of lightning.

1.5 PRESENT OBJECTIVES

This dissertation reports on research which enlarges our understanding of thunderstorms over Alberta forests to the extent that their behavior is governed by both the meso-climate of the layer above the forest canopy and the structure of the meteorological fields within an

atmosphere which favours cumulus development. In its quest to see more of the treasures of cumulonimbus clouds, this analysis has been orientated to answering the following questions, namely:

1) What are the spatial, temporal and physical characteristics of thunderstorms which occur over Alberta forests?

2) Can the climatological processes be modelled to explain the trends of thunderstorm development to provide an explanation for the foregoing patterns?

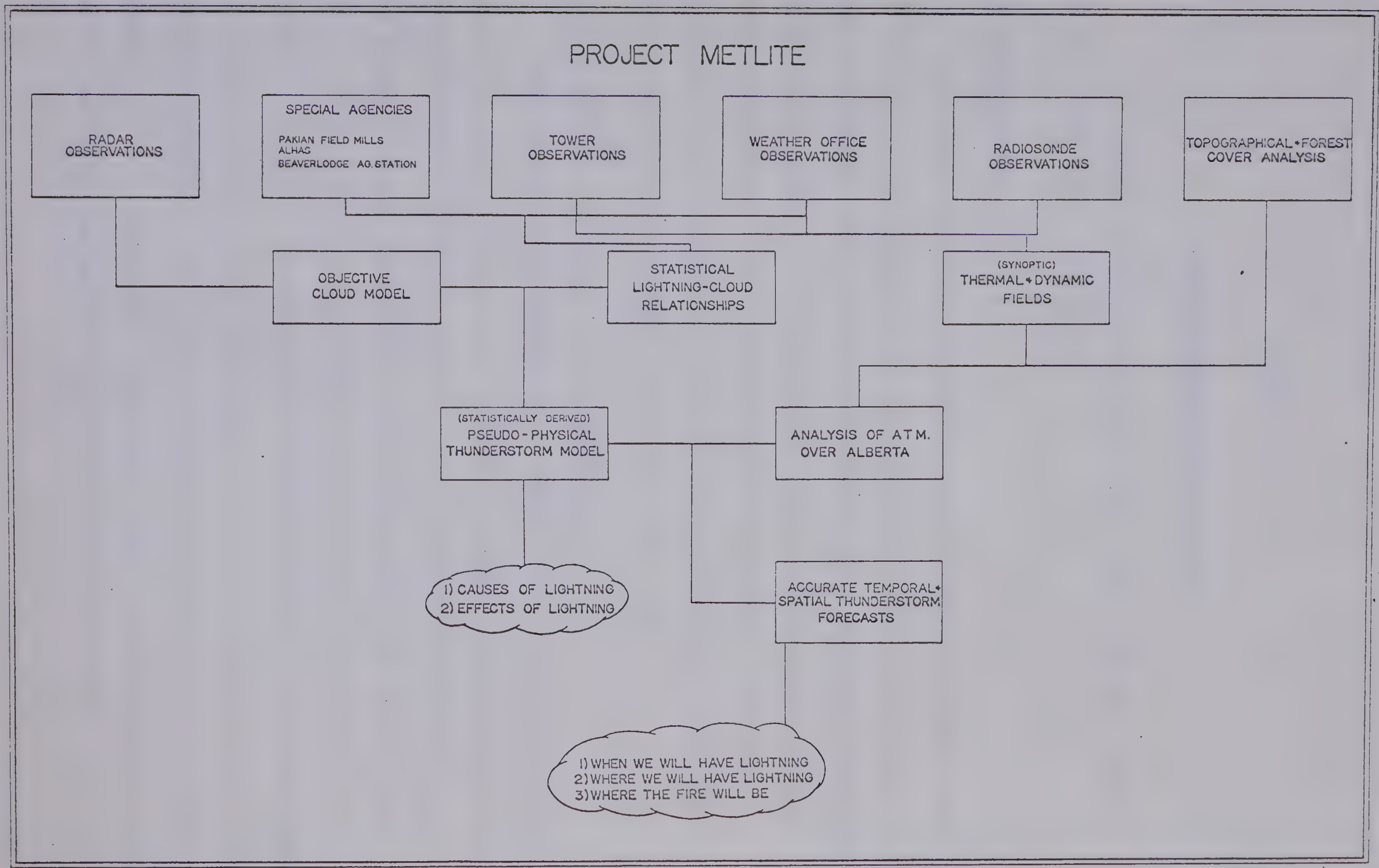


Figure 1.6 A FLOW DIAGRAM OF A LONG-TERM SOLUTION TO THE PROBLEM ON THUNDERSTORM PREDICTION.

CHAPTER II

STATUS OF CONTEMPORARY THEORY

He bindeth up the water in his thick clouds; and the cloud is not rent under them (Job 26:8)

2.1 INTRODUCTION

The 'thick cloud', now known as the cumulonimbus, can be recognized by its unique shape, its ability to retain large quantities of water in both the liquid and solid phases and its association with hail, lightning and thunder. As much research has been undertaken to establish the dynamics of thunderstorms and the atmospheric conditions resulting in their development, the following review will be cursory, emphasizing only those studies relevant to this study.

2.2 THE GENERAL CLIMATOLOGY OF THUNDERSTORMS

Thunderstorms are recognized as charge generators which are necessary to maintain the potential gradient between a relatively positive ionosphere and a negatively charged earth. Downward transfers of positive charge from the ionosphere to the earth weaken this potential gradient. If the spherical capacitor consisting of the earth and the ionosphere is to retain the observed equilibrium gradient, a mechanism capable of reversing the downward transfer of positive charge must also operate. As measurements show, fair weather currents weaken the earth-ionosphere gradient. It was postulated (Webb, W.L., 1969) that the thunderstorms must be partially responsible for maintaining this gradient.

Since charge in the ionosphere tends to be distributed quasi-uniformly, we conclude that the spatial variations in the isoceraunic levels among various stations which result primarily from the meteorological conditions present in the atmosphere and the physical characteristics of the underlying terrain.

Because thunderstorms are a very impressive sight, people have studied the spatial distributions of thunderstorm occurrence for a long period of time. Many of these studies have been hampered by the lack of a dense standardized global observing network. Figure 2.1 shows a late 19th century map of global thunderstorm activity. The lack of observing sites at higher latitudes result in errors in the patterns north of 40°N. Recent observations confirm the patterns Bartholomew has shown to exist in the lower latitudes. The maxima bordering the equator combined with

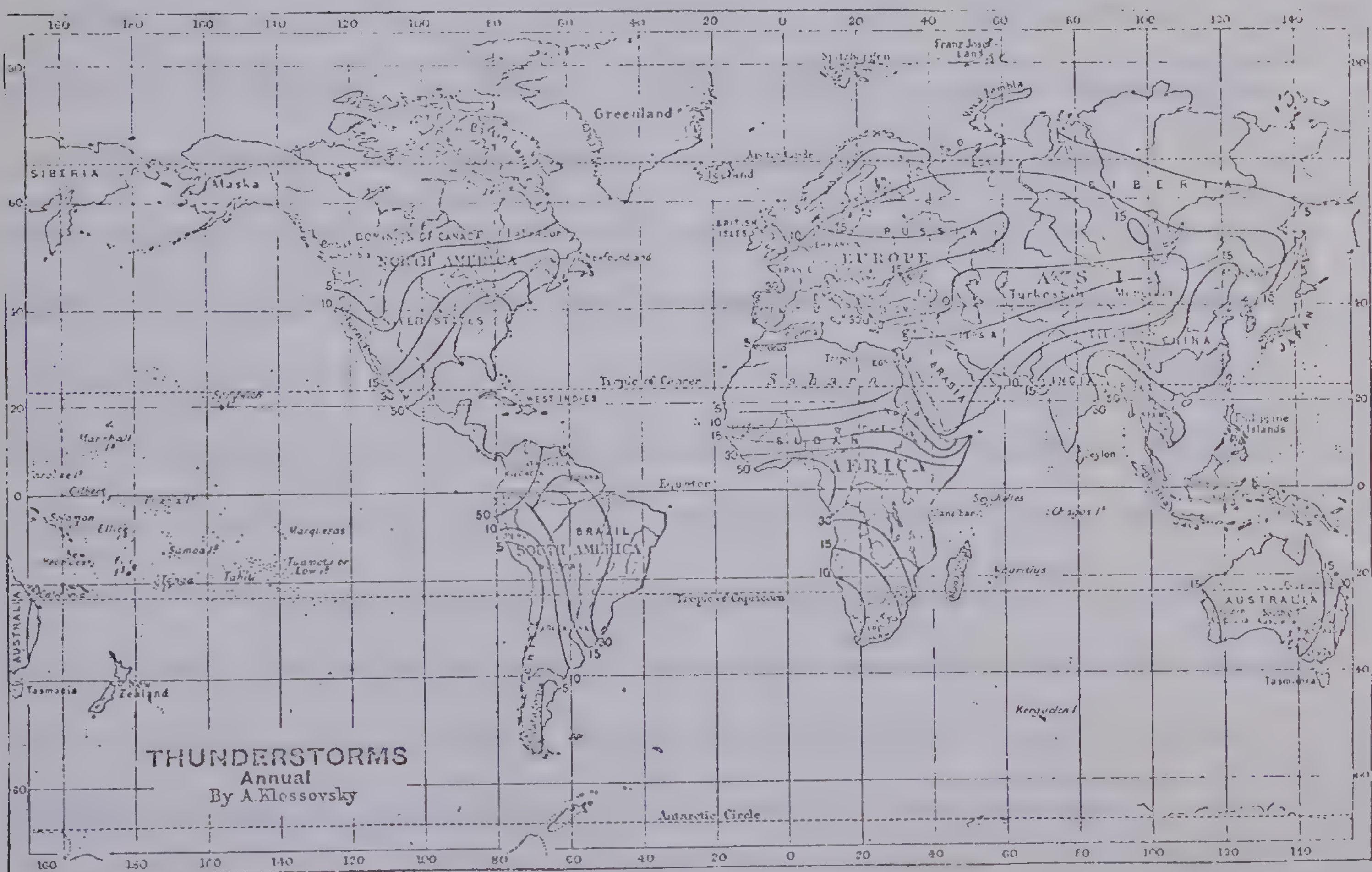


Figure 2.1 THE ANNUAL DISTRIBUTION OF THUNDERSTORMS FOR THE WORLD. (after Bartholomew, 1899.)

the minima present over the arid areas suggest that both temperature and high humidities assist thunderstorm formation.

In a more recent analysis Brooks (1925) estimated that 44,000 storms occur daily resulting in 100 lightning discharges per second. The island of Java, where at an average location an observer will hear thunder 61 per cent of the days of the year, is reputed to be the most thundery place in the world. The region of Transvaal in South Africa, which has an annual mean of 20 cloud-to-ground flashes per square mile, represents the most electrically active of the documented areas of the world.

Figure 2.2 displays the mean annual number of days with thunderstorms over Canada and the United States. The importance of the temperature-moisture combination is again demonstrated by the maximum isoceraunic levels present in the southeastern States. The northward advection of tropical air from the Gulf of Mexico appears responsible for this maximum. The large number of thunderstorm days present in the arid region just to the lee of the Continental Divide implies that the Cordilleran formation affects the development of cumulonimbus. A map of annual hailstorm frequencies is given in Climate and Man. The fact that the center of the area of highest hailstorm occurrence is displaced almost 100 miles to the east of the thunderstorm-day maximum present on plate 4 of the Water Atlas of the United States (Miller et al, 1963) implies that the mechanism whereby orographic systems affect the development of convection must either behave differently or act over longer periods of time for hailstorms than it does for thunderstorms.

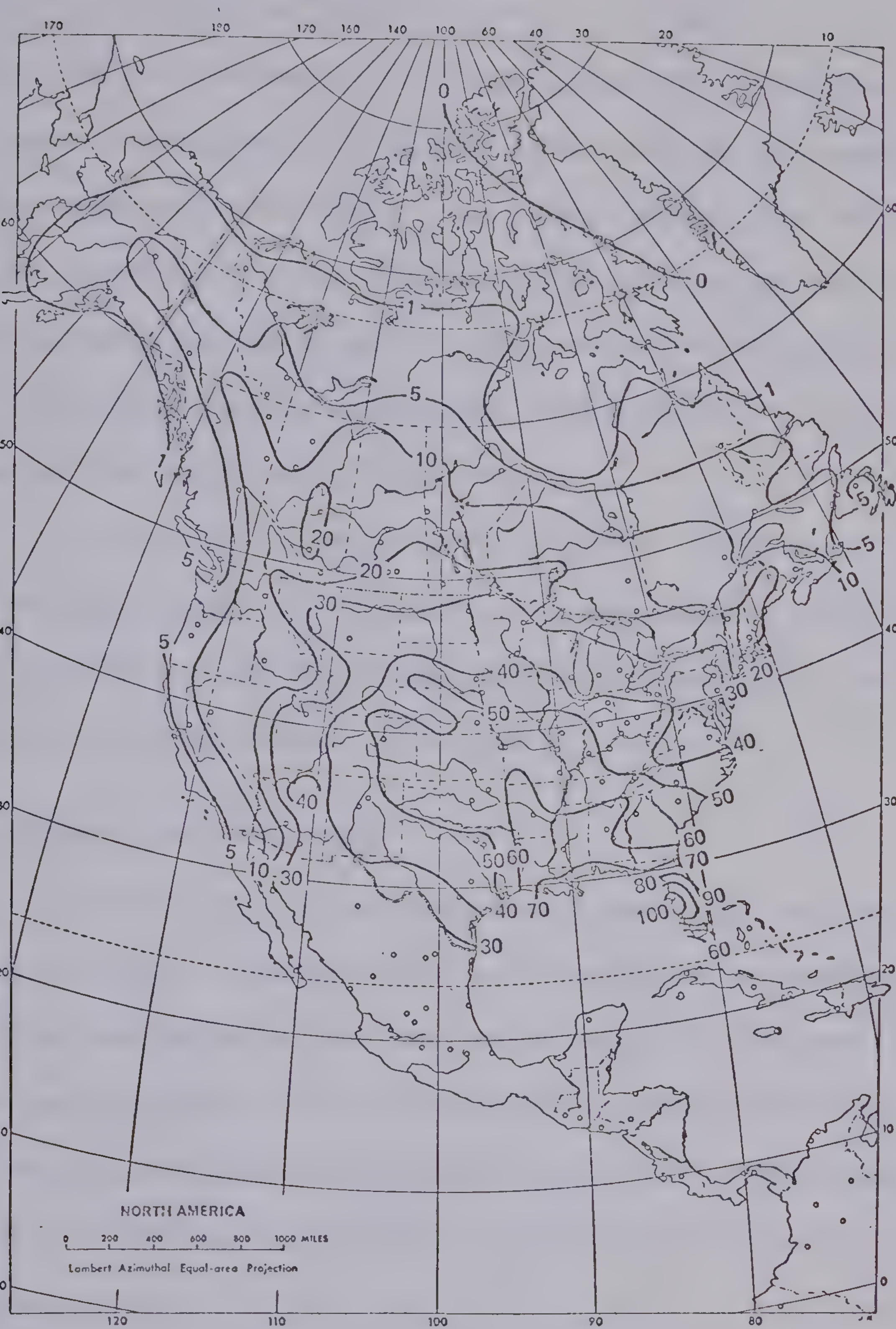


Figure 2.2 THE MEAN ANNUAL NUMBER OF DAYS WITH THUNDERSTORMS. (after Longley, 1970.)

A detailed series of charts based on observations taken at Alberta Forest Service lookouts were constructed by J. W. McLean (1968). Figure 2.3 shows the complex patterns of thunderstorm occurrence in Alberta. Three definite maxima exist: one in the western Whitecourt forest, another in the central Peace River forest, and the third in the western Athabasca forest. The fact that areas of maximum thunderstorm activity and major topographical features in northern Alberta have the same horizontal dimensions suggests topography may be partially responsible for the existence of these maxima.

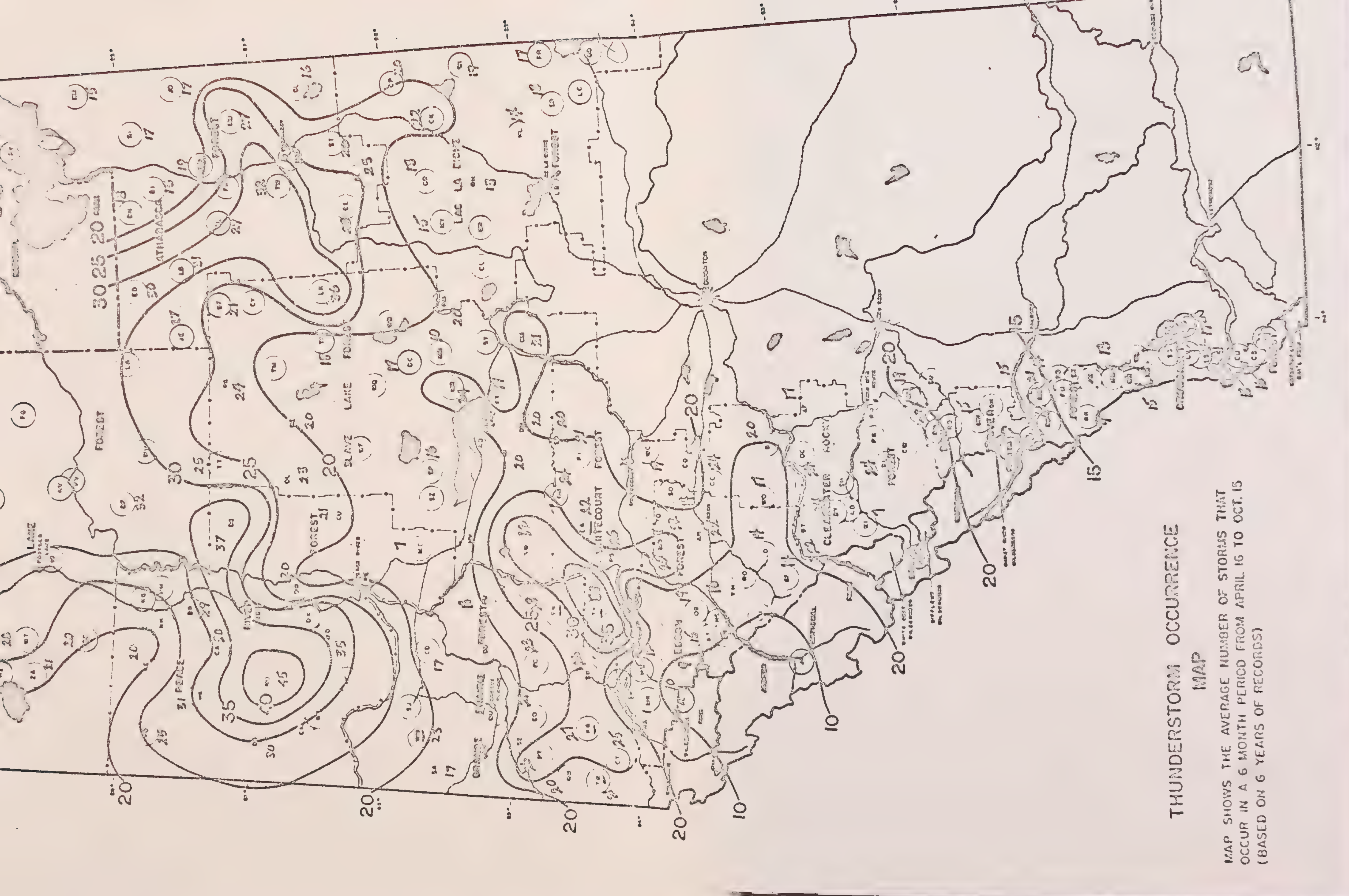
The studies of Powell (1961) and Paul (1967) have related hailfall to physiography and orography. It appears that some of the mechanisms responsible for the production of hailstorms may also affect the formation of thunderstorms without hail.

2.3 THUNDERSTORM PREDICTION

In all current operational techniques for forecasting thunderstorms empirically derived formulae are employed to some extent. Three different approaches to the forecast problem are discussed below. The first two approaches which use empirical formulae and models explicitly are generally employed operationally, while the third approach is included as a new avenue which has the potential for solving prediction problems.

The first approach, known to many as synoptic forecasting, is one employed in most Canadian weather offices because it allows a rapid and accurate assessment of the current weather.

Synoptic forecasting requires an evaluation of the atmosphere in terms of partially subjective concepts. These hypotheses include



ANNUAL NUMBER OF THUNDERSTORMS FOR ALBERTA BASED ON STORM REPORTS COLLECTED BETWEEN 1962 AND 1968. (after McLean, 1968.)

constructs such as fronts, trowals, etc. The existence and location of these constructs in the forecaster's analysis depends on his individual concepts relative to the necessary conditions for the existence of the construct. This subjectivity in the analysis for the existence of . these features and the assumption made by some forecasters that thunderstorms can be forecast on the basis of these constructs without considering low level moisture and wind fields represent the two major weaknesses of the approach. A third weakness inherent in the synoptic approach to thunderstorm forecasting arises from the scale of meteorological phenomena being considered. Frequently meso- and micro-scale events initiate the growth of thunderclouds. Synoptic scale constructs are inadequate for forecasting phenomena occurring on these smaller scales. Models such as these are not without many advantages. The two major advantages arise from the physical processes connoted by these constructs. As a result they provide a quick insight into the processes occurring within the atmosphere and a rapid medium for communicating the effects these processes will have in initiating the thunderstorms occurring on a certain day.

The second approach, known as the objective or semi-objective technique, can take several forms. In general it involves the calculation of indices such as the ones devised by Sly (1965) or Miller (1967). These indices are derived from empirical formulae which combine certain relevant observable parameters of the atmosphere. By comparing the magnitude of an index, calculated from the actual or forecast values of the parameters for a given day, to a critical value determined from research or experience, a conclusion regarding thunderstorm formation can by drawn. Miller (1967) describes another technique presently being

used in the Prairie Weather Central (Davis, 1970). This technique involves the analysis of meteorological fields at various levels. The intersections of jet streams and ridges of maximum moisture and temperature fields are used in locating the areas of thunderstorm development. Although he suggested many sufficient conditions for thunderstorm development, Miller found, as his predecessors in the past have found, that necessary conditions for thunderstorm development are hard to define.

Problems arise if the results of objective techniques are not subjectively evaluated. An objective approach often results in a number or a value fact (Fisk, 1968) which provides an indication of the likelihood an event will occur. The number can be used most effectively if the events leading to the value fact are also considered. The Slydex provides an example of this. A ridge of high pressure resident over Alberta in July can result in values of the Slydex (Sly, 1966) which are associated with storm development. Subsidence above 500 mb associated with this ridge will inhibit convective activity to the extent that lightning will not occur. It is evident that the use of objective techniques or synoptic constructs has limitations since these are unable to incorporate all the processes involved in the development of a thunderstorm.

This thesis infers that topography through the generation of peculiar microclimates partially determines the development of Alberta thunderstorms. Although spatial variations of the critical values of the Slydex and other indices tend to confirm this premise, small scale processes are not adequately incorporated into semi-objective techniques. Limited knowledge about the effectiveness of the coupling between the boundary layer and the layer of free convection prevents this process from being included in objective analytical techniques.

Objective techniques can provide probabilities which aid users in making decisions based on specific forecasts. The United States Weather Bureau is currently providing forecasts which give the probability of thunderstorm development at specific localities. Two types of probabilities exist, namely subjective probabilities which express the confidence a forecaster has in his prediction and secondly the objective probabilities which summarize what percentage of the area is likely to be affected by thunderstorms. Longley and Thompson (1965) quantified the effects of synoptic features by gradients and vorticities and derived probabilities of thunderstorm development.

The advantage of objective techniques lies in their adaptiveness in computer programs. A well designed computer program could make available in several minutes not only the type of probabilities derived by Longley and Thompson but also the results of an objective technique based on the principle of event causality rather than value fact causality. The long-term plan proposed in Chapter I under the title of Project Metlite represents an approach designed to develop a forecast technique based on both event and value fact causality.

The advent of the computer has led to the development of many models simulating thunderstorms and hailstorms. Although these models have been used to study the behavior of individual storms and to evaluate the results of cloud-seeding experiments, little has been done to incorporate them into a prediction technique. Although this approach has not been tried as far as is known, the development and dimensions of a model thunderstorm immersed in the meteorological fields forecast for the afternoon could be calculated using a hailstorm or thunderstorm model. Since many scales of meteorological processes would be

interacting, a dense observational network would be required to provide initial conditions for the model in order to obtain an accurate forecast of the exact location of a thunderstorm in time and space.

2.4 THUNDERSTORM ENVIRONMENTS

Since the 1880's when J. P. Finley first attempted to predict tornadoes (House, 1963), meteorologists have been in search of the characteristics of environments which lead to thunderstorm formation. It is universally recognized that the three necessary conditions within the atmosphere are:

1. instability in the lower and mid-troposphere. This instability is necessary because it provides rising thermals with the kinetic energy necessary to reach levels where precipitation-generation mechanisms can form lightning and hail. The eddy derives this kinetic energy from the buoyancy forces acting on it. The buoyant forces result from the positive temperature difference developing between the eddy and its environment as the eddy rises.
2. moisture in the lower troposphere. A rising eddy must possess some moisture if a cloud is to be formed. In cases where very little moisture is available, cumulonimbus clouds have high bases and produce very little precipitation. Braham, Jr. (1952) postulated that the water vapour drawn into the storm maintains the downdraft. Although this postulate suggests that a moist mid-troposphere assists in the formation of thunderstorms, other authors (Newton, 1967) suggest that dry conditions in the mid-troposphere intensify

the downdraft. Newton and Fankhauser (1964) suggest that thunderstorms travel in a trajectory which carries them over areas with the strongest moisture fluxes.

3. source of vertical velocities in the low-level. These upward motions arise from energy sources in the boundary layer which are derived from thermodynamic and dynamic processes. Frontal discontinuities, orographic lift, differential surface heating and low-level convergence represent the best known of these processes.

Braham, Jr. and Draginis (1960) found that elevated heat sources play a major role in the formation of cumulonimbus clouds. Carlson and Ludlam (1967) found plateaus acted as heat sources. Their study, which also considered the effects of winds in initiating convective storms, led them to conclude that the occurrence of severe storms demands a peculiarly favourable combination of geographical features and the atmospheric flow pattern. The elevated heat source occurs over elevated terrain where slope, albedo and aspect effects are combined to give rise to intense thermals. A slope assists in the formation of updrafts because the sun's rays falling nearly perpendicularly increase surface heating. Over high terrain where trees are either sparse or non-existant low albedoes result in increased surface heating. Such excessive heating resulted in the intense updrafts Braham, Jr. and Draginis (1960) found over mountain peaks.

The effects of heating are most noticeable over high terrain. Consider ten degrees of heat added to two locations in the atmosphere, one overlying a low-lying plain and the other over a hill. Above the low-level heat source, convective and radiative processes transfer heat

aloft and modify the atmosphere in which the buoyant bubbles forming over the plain will rise. Because the environment surrounding an elevated heat source is relatively immune to modification by heat transfers the ten-degree temperature difference between air immediately above the source and the environment in which it grows will remain the same. The larger anomalies present over the elevated heat sources result in more buoyant thermals and the formation of early afternoon mountain cumulus. The aspect of the slope causes the diurnal variations observed in the location of maximum surface heating and maximum vertical velocities.

Valleys are sources of thermal energy. Air parcels remain in these valleys absorbing heat from a valley's sides and bottom. When these parcels become sufficiently buoyant they break away from the valley and rise rapidly. When eddies of this nature are released they result in very energetic high-velocity thermals which can penetrate into the unstable layers aloft. A similar effect is found in certain synoptic (Miller, 1967) or geographical (Carlson and Ludlam, 1967) situations where an inversion caps the low-level vertical motions until they become energetic enough to penetrate into the layers of instability aloft.

The effects of wind shear have often been studied in relation to hailstorm formation. Dessens (1960) suggested that strong winds between 7000 and 12000 meters determine the transformation of thunderstorms into hailstorms. Das (1962) and Thompson (1970) have pointed out the importance of strong vertical wind shears and their ability to organize the circulation of cumulonimbus clouds, thereby causing the devastating quasi-steady-state hailstorms. Very little work has been done regarding the relationships between wind shears and thunderstorm formation although Sly (1966) does suggest that wind shear affects the development of

Alberta thunderstorms. Pitchford and London (1962) suggest that a low-level jet is responsible for the development of nocturnal thunderstorms in the mid-western United States.

The barrier effect is another recognized source of vertical motions resulting from topographic or orographic features. As a stream of air flows towards a hill or mountain it is either forced upwards over the obstacle or flows around the obstacle. Although much of the air flows around isolated peaks some air is forced upwards, resulting in the motions necessary to raise air into unstable layers present aloft. Convergence in the micro-scale circulations which evolve over certain geographical features during the day can form thermals or eddies energetic enough to penetrate into the layer of free convection. Endlich and Mancuso (1968) showed that upper-troposphere divergence is a good indicator of severe storm activity. Divergence in the upper-troposphere must be compensated for by low-level convergence, according to Dynes' compensation law. These deductions imply that synoptically induced low-level convergence is another trigger mechanism.

The flow of air over major orographic systems such as the Rocky Mountains leads to streaming in the air immediately to the lee of the mountains. The effects of mountains on convection, noted in section 2.2, appear to be the consequence of this streaming. Wave formation has been recognized on the planetary (Queney, 1948) and the micro-scale (Küttner, 1939). Dirks et al (1967) have postulated from the equations of motion and an analysis of satellite photos that under conditions of low stability and weak wind shear a quasi-horizontal meso-scale wave affects thunderstorm development. These waves induce vertical motions which restructure the meteorological fields present in the lee of the Rocky

Mountains. This restructuring leads to the formation of environments where the growth of immature cumulus congestus is either accentuated or suppressed.

Other characteristics of the atmosphere may serve as indicators of approaching severe storm weather. Thickness advection, the height of the zero degree wet bulb temperature isotherm, changes in the surface pressure pattern, positive vorticity advection at 500-mb and the 500-mb 12-hour height change are all parameters which may indicate the onset of thunderstorms.

2.5 THUNDERSTORM MODELS

A review of the current models of thunderstorm development is necessary before rational explanations of the observed behavior of thunderstorms can be provided or the significance of reliable indicators of thunderstorm activity can be examined. Throughout this dissertation the classical work of Byers and Braham (1949) will be referred to. After having analyzed a very comprehensive collection of information they postulated that thunderstorms pass through three distinct phases of development, namely:

1. the cumulus stage. In this phase most of the air within the cloud is rising and very little electrification has taken place. Measurements have shown that the base generally has a net negative charge.
2. the mature stage. The storm is said to have entered this stage when the liquid water (known as the water burden) over the core of maximum updraft begins to fall through the base of the cloud to the ground. This occurs when the pull of gravity on the individual droplets exceeds the lifting forces

exerted by the updraft. It is early in this stage, coincident with the formation of a downdraft within the cloud that charge separation mechanisms first operate. Kuettner (1950) studied the distribution of charge within mature cumulonimbus clouds. Figure 2.4 portrays the charge distribution within mature cells.

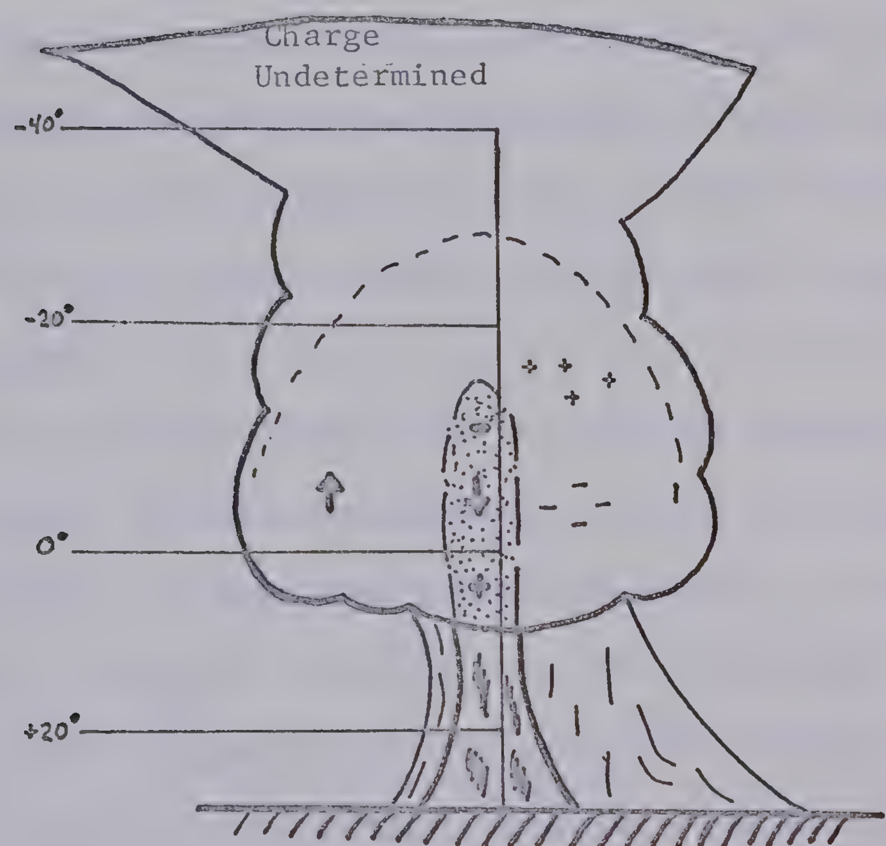


Figure 2.4 THE DISTRIBUTION OF CHARGE WITHIN A MATURE CUMULONIMBUS. (after Kuettner, 1950). In the strong downdraft, which is marked by dots, a strong positive charge forms near the cloud's base. Outside the downdraft a positive charge center exists below the -20°C isotherm while a negative charge center exists at -5°C. The area of intense updraft has a variable charge.

3. the dissipative stage. In this phase the cloud is dying because a) the water burden falling through the updraft has completely eroded the area of ascending air or b) the excessive growth of the downdraft has cut off the supply of moist buoyant air required to maintain the updraft.

Recently, in-cloud measurements have provided further information relative to the charge distribution within early mature cumulonimbus. The presence of a small positive space charge present in the leading edge of most thunderclouds is felt to initiate the first in-cloud charge transfers. The work of Workman and Reynolds (1949) demonstrates that cloud-to-cloud lightning and the first visible precipitation occur simultaneously while cloud-to-ground discharges commence several minutes later. This observed sequence of events confirms the suggestion that in-cloud charge transfers are the first to take place within thunderstorms.

The above-mentioned model, held as a working hypothesis by many meteorologists, has been challenged by a school of thought led by Vonnegut. Rather than attributing charge generation to precipitation processes in the cloud, he hypothesized that the thermals carry positive ions into the upper part of the cloud while negative ions descend from the ionosphere through the intermediate atmosphere and the outer edges of the cloud to the cloud's base. This school, which suggests that electrification in clouds leads to the formation of precipitation (Moore et al, 1964), points to the rain gush and the ability of cumulus clouds to assume the charge of ions being emitted from a surface source (Vonnegut and Moore, 1958) as justification for their conclusions. Emphasis of the importance of the physical constitution of the physiography

could provide an explanation for preferred areas of lightning strikes and storm development. Perhaps the prospector from northern Alberta who went hunting for mineral in locations where lightning struck had recognized the ramifications of this theory.

Laboratory experiments simulating the precipitation processes of thunderclouds have resulted in many theories. Although the validity of generalizing these results to the uncontrolled environment is a major question in establishing electrification processes in thunderstorms, nearly all processes are felt to operate during the life cycle of these storms. In this dissertation it is assumed that the actions of precipitation processes are responsible for generating electric fields throughout the mature stages of thunderstorm development. This assumption is based on the absence of any observations of negative charge fluxes in the periphery of the thunderclouds in spite of the many in-cloud measurements which have been made (Byers and Braham, 1949; Kasemir, 1968). This absence is evidence against Vonnegut's theory. In several situations where the point discharges at the surface provide an alternate explanation of the observations these explanations are given.

2.6 LIGHTNING PRODUCTION

Thunderstorms transfer charge downwards during a cloud-to-ground lightning strike. Such a flash occurs when the potential gradient, which exists in the subcloud layer as a negatively charged cloud base, moves over the positive earth, exceeds the dielectric constant of the layer. Measurements of the fine structure of these discharges indicate that a discharge or flash is composed of a series of streamers descending to the ground and return strikes which neutralize the pockets of negative space charge present in the thundercloud's base (Chalmers, 1967). Pierce (1970)

outlines the significance of the number of return strokes occurring in a dielectric breakdown. He shows that the proportion of cloud-to-ground strikes increases north of the equator with increasing latitudes while the frequency of return strokes per flash decreases with increasing latitude. Brooks and Kitagawa (1960) have shown that the number of return strokes is higher for thunderstorms which form on the surface of cold fronts. This dependency suggests that the energy sources initiating lightning storms are important in determining the structure of the storm and the damage it is capable of doing.

During the return stroke, as current rushes through the tree's roots and trunk it heats these resistant conductors. Under dry conditions the tree's temperature will exceed the kindling temperature and the wood bursts into flame. This aspect of lightning fires is currently under investigation by Project Skyfire personnel (Taylor, 1969). It has been observed[1] that large potential gradients develop in the immediate vicinity of an object in which large charges are induced. In a forest the heating associated with the breakdown of these gradients, which must form when lightning strikes a tree, may initiate fires in the dry duff.

The energy transfers associated with lightning play a minor role in the energy budget of a thunderstorm. They do, however, play a major role in the maintenance of the balance of nature. Komerack's ecological study (1968) suggests that lightning-caused fires may be needed to destroy trees. By this destruction they promote forest generation and provide food sources for the small birds and insects necessary to maintain

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[1] private communication with Mr. C. M. Mitchell, staff engineer of Calgary Power.

a balance in the population of forest wildlife. Evidence that lightning is required to maintain the electrical balance between the earth and the protective ionosphere has been referred to earlier. It appears that lightning, although known only as a terrestrial phenomenon, maintains balances associated with the orderliness of the cosmos.

CHAPTER III

ANALYTICAL TECHNIQUES

Canst thou send lightnings that they may go and say unto thee, Here we are? (Job 38:35)

3.1 INTRODUCTION

The phenomena responsible for lightning and lightning storms have remained in part a mystery to man. Although he has remained almost helpless either to cause or to control lightning, modern man has attained some insight into its causative factors. However a complete exposition on the subject does not appear to be forthcoming. Consequently, as with most students of the phenomenon, the author has sought to contribute to the field by his own limited approach.

This study employs the climatographic method. Elementary statistics are used to examine the temporal and spatial distributions of thunderstorm characteristics. Correlations between these characteristics and geographical features are sought. Mechanisms present or possibly present in the physical world are modelled to explain the observed relationships.

3.2 DATA SOURCES

Nineteen thousand storm reports collected by the Alberta Forest Service between the years of 1962 and 1968 inclusive are used throughout this analysis. These reports were completed by lookout operators scattered throughout 150,000 acres of Alberta forest. The author used the records after they had been coded and transferred to magnetic tape.

Form FP 38 (FSR 3)

FOREST COMMUNICATIONS

SPEED, SERVICE AND ACCURACY

NUMBER	STN.		PLACE OF ORIGIN	DATE	TIME

STORM REPORT

A. ____________ Storm No.

B. ____________ Date and Time First Obs.

C. ____________ Direction (Degrees) First Obs.

D. ____________ Distance First Obs. Allow 5 Sec/mi.

E. ____________ Distance Last Obs. Allow 5 Sec/mi.

F. ____________ Date and Time Last Obs.

G. ____________ Direction (Degrees) Last Obs.

H. ____________ Number of Strikes (Cloud to Ground Only)

I. ____________ Type of Lightning Chain / Sheet / Both

J. ____________ Condition of Strikes Dry; Wet / Both; Unknown

K. ____________ Precipitation Nil; Light / Medium; Heavy / Unknown

L. REMARKS ____________

Figure 3.1 FORM USED BY ALBERTA FOREST SERVICE PERSONNEL TO REPORT THUNDERSTORM ACTIVITY.

Figure 3.1 shows a storm report. This form was completed, based on a very practical definition of a thunderstorm, namely: a thunderstorm is any cloud or cloud complex which produces lightning, thunder or hail. The data used in this analysis consisted of the operator's observations of:

1. the onset time of the thunderstorm. This refers to the date and the time (in MST) when the storm initially displayed its thunderstorm qualities to the observer.

2. the departure time of the thunderstorm or the time when the thunderstorm either died away or moved out from the observer's view.

3. the direction of the storm from the observer when it was first observed by the lookout operator. This will be referred to as the initial bearing or the angle of approach[1].

4. the total number of cloud-to-ground discharges emitted by the storm while it remained in the observer's view.

5. the character of the lightning strikes associated with the storm. Three types of discharges are recognized, namely:

   a) the dry flashes. These cloud-to-ground discharges come from storms which are not producing visible precipitation at the surface.

   b) the wet-dry flashes. This term applies to lightning associated with storms which produce cloud-to-ground discharges both inside and outside the precipitation area.

   c) the wet flashes. This characteristic is attributed to

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[1] on several graphs in Chapter 5 it is also referred to as the angle of attack. All three terms are synonymous.

lightning strokes from storms which produce all their cloud-to-ground discharges within the rain area.

Observations taken at stations operated by the Meteorological Service of Canada were also used. Hourly Data Summaries, which supplied information regarding the frequency of thunderstorm and hail occurrences at hourly intervals over a ten-year period, were also used.

3.3 BIASES IN THE STORM REPORTS

Because of the nature of the observations and the observer's work schedule the storm reports obtained from the Alberta Forest Service contain some biases. The observer, whose primary duty is to observe and report the occurrence of forest fires, is obliged to complete reliable observations of all lightning-produced storms in his field of view. Variations between observers are visible in Figure 3.2. Although observations of onset times are to be reported to the nearest five minutes, three definite biases appear present in the graph of the number of reports plotted against the minutes after the hour on which these observations were made. More storms are reported at 10, 15 and 30 minute intervals. These preferred times are biases introduced by the less conscientious observers who tend to approximate onset times. Since onset times are used in calculating averages and constructing frequency distributions the effects of this bias should be small.

Another bias is introduced by the observer's schedule of activities. As economic factors allow the Alberta Forest Service to employ only one operator per lookout, very few observations are taken during the interval from sunset to sunrise. Lawford (1970b) has compared the results of Alberta Forest Service observations with storm observations

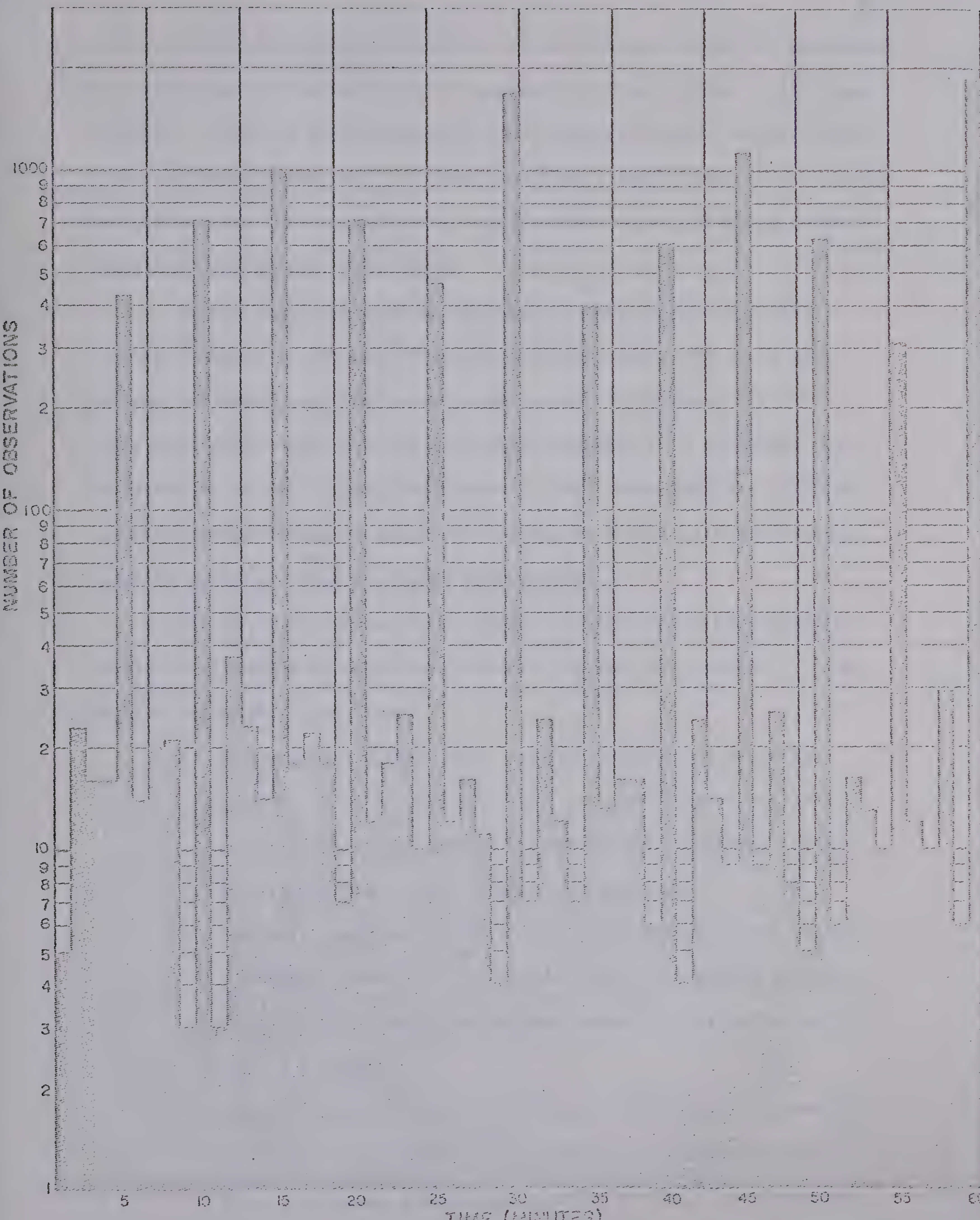

Figure 3.2 THE NUMBER OF STORMS REPORTED EACH MINUTE AFTER THE HOUR.

taken at the Meteorological Services' weather observatories and concludes that this bias overemphasizes the nocturnal minimum at nearly all forest lookouts. Although this systematic error exists it does not affect comparisons among stations. It does introduce a small error which must be recognized when one is considering the absolute values of storm characteristics such as mean onset time.

Preferred directions were present in the records of initial bearing. Biases at 10, and 45 degree intervals appeared in the data. In order to compensate for these biases smoothed frequency distributions were used. The original data were tabulated in a frequency distribution based on a ten-degree interval. The unsmoothed distribution was then passed through a symmetric triangular filter with a 40-degree width to produce a more realistic distribution.

The absolute values of the number of strikes per storm must be critically examined as many observational problems are present. These problems commonly arise from:

1. the observer's work load. As the counting of cloud-to-ground discharges is only one of the observer's duties, other problems may demand his momentary attention, thereby causing him to miss some of the flashes.
2. the rain curtain. Falling rain often obscures much of the lightning present in the hinder parts of a mature thundercloud. This results in underestimates of the actual number of strikes.
3. the time of the storm's occurrence. It is common knowledge that lightning flashes are visible over longer distances at night. Because a larger proportion of the strikes present

in a nocturnal storm will be observed, this bias will affect comparisons between stations with a large number of night time storms and those with only afternoon thunderstorms.

Many other biases are introduced depending on the lookout's exposure. The problem of determining whether strikes are dry or wet-dry for a storm with only very weak precipitation located ten miles from a lookout exemplifies another problem present in documenting thunderstorms. The present climatographic analysis is based on the assumption that the foregoing biases are randomly distributed throughout the province. The results of independent sampling used to check many of the spatial distributions contained in Chapters 4, 5 and 6 confirmed the validity of this assumption.

3.4 THE GEOGRAPHICAL FEATURES OF ALBERTA FORESTS

The area under the jurisdiction of the Alberta Forest Service is subdivided into eleven forested areas. These forests are bounded by the 60th parallel in the north and the 49th parallel in the south. Except for the southern forests where the Continental Divide forms a natural boundary the 120°W meridian serves as the western border. In order to separate those forests characterized by rugged terrain from the forests with rolling terrain present in northern Alberta the forests are classified as either elevated or lowland forests. The elevated forests include those forests whose terrain is influenced by the orographic system to the west, namely:

1. the Bow River Forest
2. the Clearwater-Rocky Forest
3. the Crowsnest Forest
4. the Edson Forest

5. the southern Grande Prairie Forest

6. the Whitecourt Forest

This group includes most of the forested areas south of 54 1/2°N

The Whitecourt Forest is difficult to categorize but is included as an elevated forest on the basis of its mean elevation and the association of many of its southern and western lookouts with the foothills of the Rocky Mountains. The remainder of the forests outlined in Figure 3.3 compose the other group designated as the lowland forests.

This study intends to demonstrate that the distribution of thunderstorms in Alberta is affected by topographical features. The Rocky Mountain Range and the associated foothills dominate the terrain in the southern forests, while smaller topographic features are present in the northern forests. Features of note include the Birch Mountains and the Thickwood Hills in the northern Athabasca Forest, the Clear Hills in the Peace River Forest and the Swan Hills in the Slave Lake Forest.

3.5 THE CLIMATOGRAPHIC APPROACH

Climatography, a word introduced by Conrad and Pollack (1950), is used to describe the statistical approach to solving some problems of climatology. Rather than emphasizing the results as climatology does, climatography refers to a certain methodology - a statistical method designed to uncover the relationships between climatic parameters. After these interrelationships are resolved and the causative factors uncovered, inferences can be made regarding the climatic processes at work in the area.

In completing the analysis discussed in this dissertation

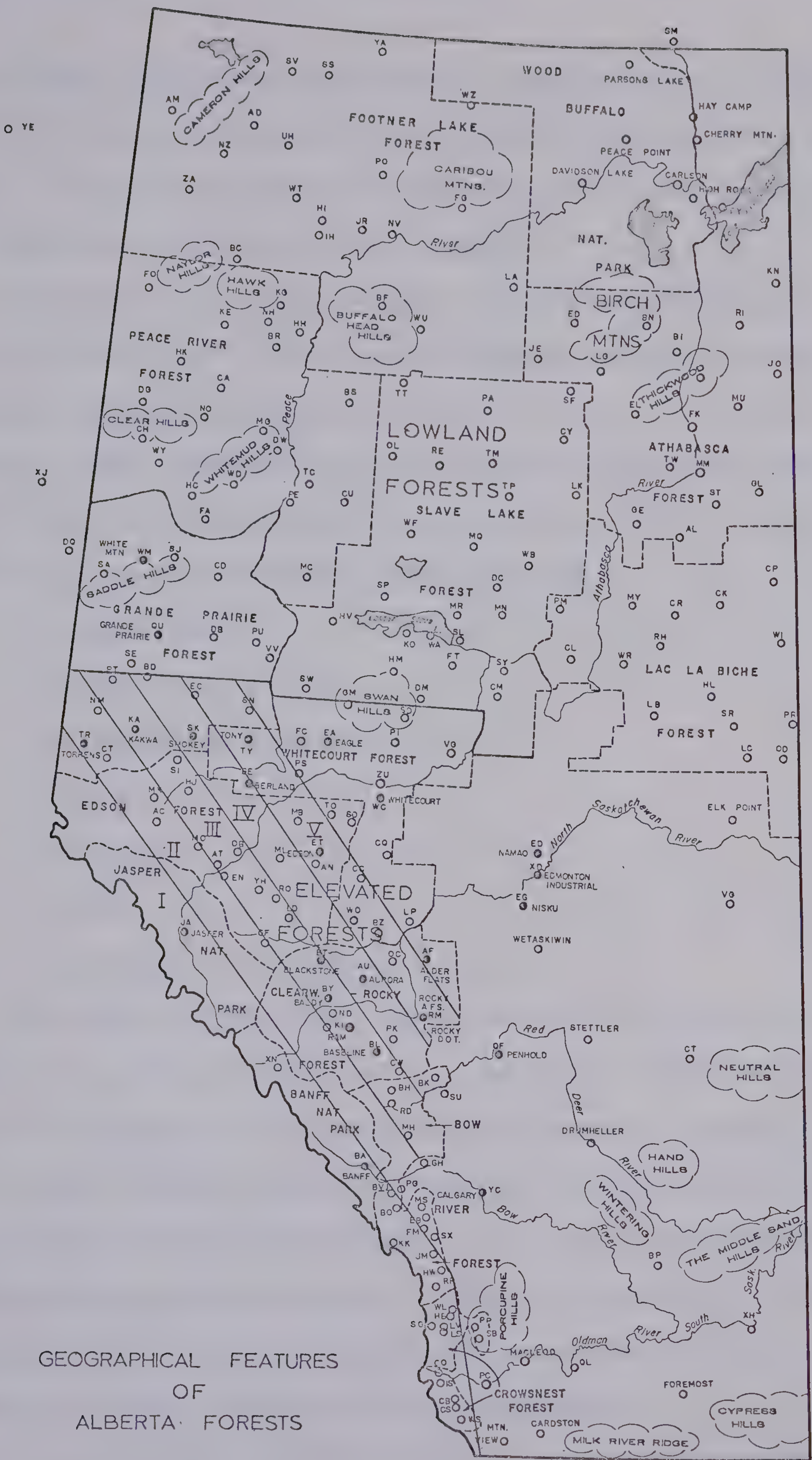

Figure 3.3 THE GEOGRAPHICAL FEATURES PRESENT IN ALBERTA FORESTS.

several analytic techniques were employed. These techniques, subsequently referred to by acronyms, will be summarized in the remainder of this chapter. The calculations were facilitated by ready access to the IBM 360/67 belonging to the University of Alberta.

The MPO analysis (Map Print Out) consisted of plotting the spatial distributions of certain storm parameters on maps of Alberta. A program was designed to calculate and print these values on a map of Alberta. After these maps were analyzed the isopleths were transferred to base maps obtained from the Alberta Forest Service. The statistical parameters analyzed in this way included:

1. frequencies
2. relative frequencies
3. cumulative frequencies
4. means
5. medians
6. modes
7. empirical probabilities

The method of independent samples was used to determine the validity of the patterns which resulted. One-half to two-thirds of the stations were randomly chosen and plotted on the chart. Although central values were often missing, and isolated extreme values vanished, the reanalyzed patterns preserved most of the gross features which characterized the original patterns. Based on the correlation between the original and the independent sample all the patterns included in this analysis are accepted as being valid and significant.

A second technique which involved the computation of correlation coefficients will be referred to as the CCC technique. In total,

79 stations were included in this analysis - 43 in the lowland forests and 36 in the elevated forests. Correlation coefficients were used to express the interrelationships between independent storm parameters as well as their dependencies on station elevation and location. Since different characteristics appear to be present for thunderstorms occurring in the southern forests, coefficients for both the elevated and lowland forests were determined.

The storm parameters subjected to the CCC technique included:

1. the relative percentage frequencies of dry lightning storms
2. the relative percentage frequencies of wet lightning storms
3. the relative percentage frequencies of wet-dry lightning storms
4. the dates of the median thunderstorm day
5. the mean storm durations
6. the average number of strikes per storm
7. the relative percentage frequencies of thunderstorms approaching from a particular octant
8. the mean initial bearings
9. the mean onset times
10. the discharge rate . This derived parameter is defined as the number of strikes occurring during a five-minute interval.

Simple correlation coefficients were calculated for each forest by first finding the sums of the cross products of the deviations. The temporary means were calculated and subtracted from each value to determine the deviations. In symbols the temporary means were calculated by:

$$T_x = \sum_{i=1}^{N} x_i \; / \; N$$

where x_i is an individual value of parameter x and N is the number of x's

and the cross products were obtained by:

$$S_{xy} = \sum_{i=1}^{N} (x_i - T_x)(y_i - T_y) - \sum_{i=1}^{N} (x_i - T_x) \sum_{i=1}^{N} (y_i - T_y)/N$$

where S_{xy} is the sum of cross products

T_y is the temporary mean of parameter y

y_i is an individual value of parameter y

The correlation coefficients were obtained by dividing the sum of the cross products by the standard deviations of x and y. In symbols

$$\gamma_{xy} = S_{xy} / \sqrt{S_x}\sqrt{S_y}$$

where γ_{xy} is the correlation coefficient between x and y

S_x is the variance of x

S_y is the variance of y

Student's t-test was used to determine the significance of these coefficients. The t-statistic was calculated from the relation

$$t = \frac{\gamma_{xy} \sqrt{N-2}}{1 - \gamma_{xy}^2}$$

The temporal structure of thunderstorm characteristics are examined by use of hourly and seasonal distributions. Both diurnal and seasonal variations are inferred from these plots by simple inspection. Autocorrelation coefficients were calculated for several of the parameters to examine the possibilities of trends and periodicities. Since a more extensive analysis using Fourier and power spectrum techniques did not reveal any significant results which were not obvious from inspection, the results will not be referred to.

The TSA (Time Series Analysis) was completed by calculating

autocovariances with lags of up to 10 days in length. The autocovariance and the autocorrelation coefficient represent the correlation existing between the storm parameter x at time t and its value at time $t+\tau$ where τ is the time lag. In mathematical symbols this can be defined by:

$$C(\tau) = \text{ave} \ \{X(t)-X(t+\tau)\} \ / \ C(O)$$

where $C(\tau)$ is the autocorrelation coefficient at lag τ,

$C(O)$ is the variance,

and $X(t)$ and $X(t+\tau)$ have been defined above.

In many cases high frequency variations and missing values in a particular series necessitated passing each series through a filter before subjecting it to the TSA technique. In order to preserve phase by reducing the variance associated with the side lobes associated with the frequency response of most filters (Blackman and Tukey, 1958) a triangular lag window with a 7-day width was used.

3.6 ANALYSIS OF TOPOGRAPHIC INFLUENCES

The ALR (Analysis to the Lee of the Rockies) was devised to uncover processes which might be causing the variations in storm parameters present in the lee of the Great Divide. The area immediately to the east of the Continental Divide was subdivided into 5 zones, each 40 kilometers in width. Means and standard deviations were calculated for storm parameters in each of the five zones. By comparing the zonal variations, inferences relative to the interactions of orographic systems and thunderstorm development were made. The zones labelled from 1 to 5 are shown in Figure 3.3.

The AEH (Analysis of the Effects of Hills) was carried out using stations on the Swan and Clear Hills. Because studies which have used individual hills in assessing the role of topography have proven

inconclusive, it was decided that large terrain features with dimensions several times larger than the phenomenon under study should be used. The Swan and Clear Hills were chosen because they lie between 55° and 57 1/2° North, so that latitudinal effects will be negligible. Each hill was divided into quadrants as shown in Figure 3.4, a northern one being the quadrant between 316° and 45°, an eastern quadrant between 46° and 135°, etc.

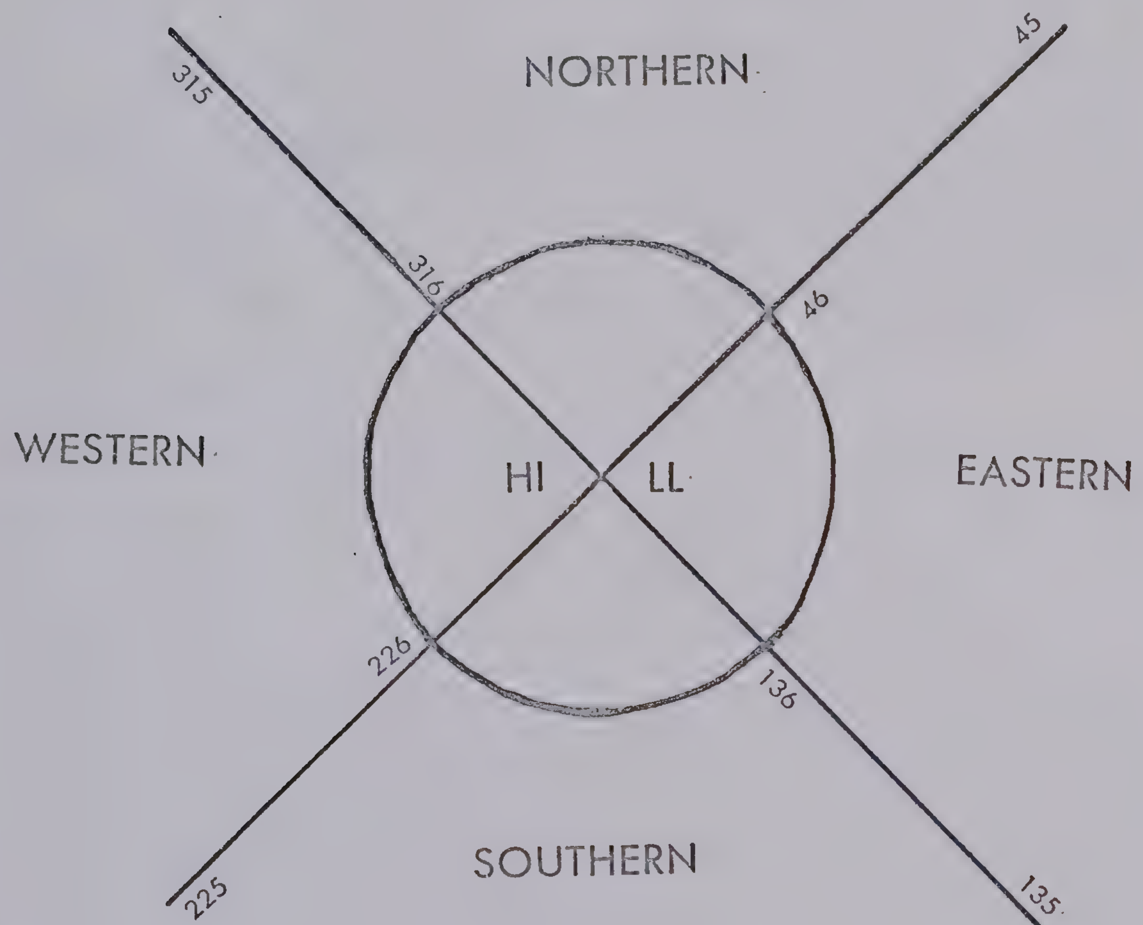

Figure 3.4 DIVISIONS USED IN AEH ANALYSIS. The four quadrants into which the Swan and Clear Hills were divided in order to examine the effects of aspect on thunderstorm characteristics.

The parameters characterizing storms on eastern slopes were assumed to be

similar to storms occurring at lookouts located on eastern slopes. The variations of storm parameters between different slope aspects are interpreted in terms of the physical processes present in the environment.

CHAPTER IV

TEMPORAL CHARACTERISTICS OF THUNDERSTORMS

The voice of thy thunder was in the heaven; the lightning lightened the world : the whole earth trembled and shook (Psalms 77:18)

4.1 INTRODUCTION

The Psalmist felt that lightning in the Holy Land was a rare event which brought with it God's anger. In the province of Alberta, lightning-producing thunderclouds are frequent in the summer skies. Paul (1967) demonstrated that severe storms in the south-central parts of the province were most frequent during the months of June and July during the late afternoon.

The input of thermal energy into the lowest layers of the troposphere and the instability of the mid-troposphere appear to control both the intensity and areal extent of cumulonimbus development. The afternoon maximum in the frequency of severe storms reflects the influence of these two controls. The accumulation of thermal energy in the boundary layer reaches a maximum during June and July afternoons. The longer days near the summer solstice allow the earth's surface to intercept the sun's radiation at larger angles of solar elevation and for longer time intervals. As absorption by the earth's surface and subsequently by the boundary layer is integrated throughout the day maximum temperatures and maximum convectional activity will likely occur near the time when the incident solar radiation equals the loss of energy from the earth's surface due to advectional, convectional and long-wave radiational heat

transfers. If meteorological processes such as the advection of temperature or moisture fields or features such as 500-mb troughs or cold fronts were the sole factors determining the spatial distributions of onset times, frequency of storm development and the other storm characteristics, we would expect thunderstorms to be, with the exception of latitudinal effects, almost uniformly distributed throughout the province. It is likely that some small longitudinal variations would exist because the mountains tend to affect the flow patterns at all levels of the troposphere.

In this chapter the temporal variations of thunderstorm development relative to the onset times and durations of thunderstorms as well as the seasonal variations of thunderstorm development are discussed. The analysis is based primarily on the storm reports collected by the Alberta Forest Service.

4.2 DIURNAL CHARACTERISTICS OF THUNDERSTORM DEVELOPMENT

The spatial distributions for mean times of thunderstorm occurrence and mean onset times throughout Alberta reflect a tendency for storm development during the afternoon. The frequency distributions of the hours on which thunderstorms are reported were analyzed and their means plotted on a map of Alberta.

Figure 4.1 displays the isochrone pattern obtained from the analysis of synoptic weather reports from Alberta and northeastern British Columbia. The means of the times of thunderstorm occurrence were calculated using 0900 MST as the zero point. Nine A.M. is the time of minimum thunderstorm activity. From Figure 4.1 it can be seen that afternoon storms tend to form in the northern parts of the province and just to the lee of the Continental Divide. The late mean times of thunderstorm

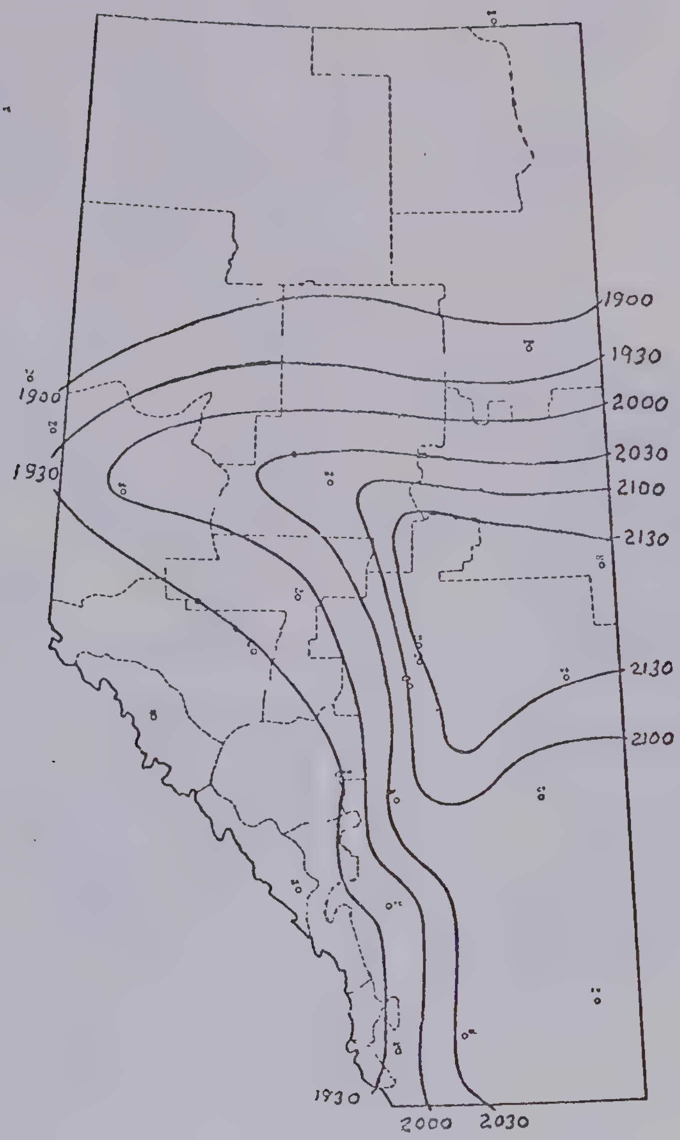

Figure 4.1 MEAN TIMES OF THUNDERSTORM OCCURRENCE. The isochrones labelled in MST are drawn at 30 minute intervals.

occurrence in east central Alberta result from the eastward translation of atmospheric instability and thunderstorms during the afternoon. The influence of the Rocky Mountains on thunderstorm activity results in isochrones which are approximately parallel to the Continental Divide.

With reports of thunderstorms from the Alberta Forest Service of which very few are nocturnal, using 0000 MST as a zero point for the calculations results in small biases and representative means.

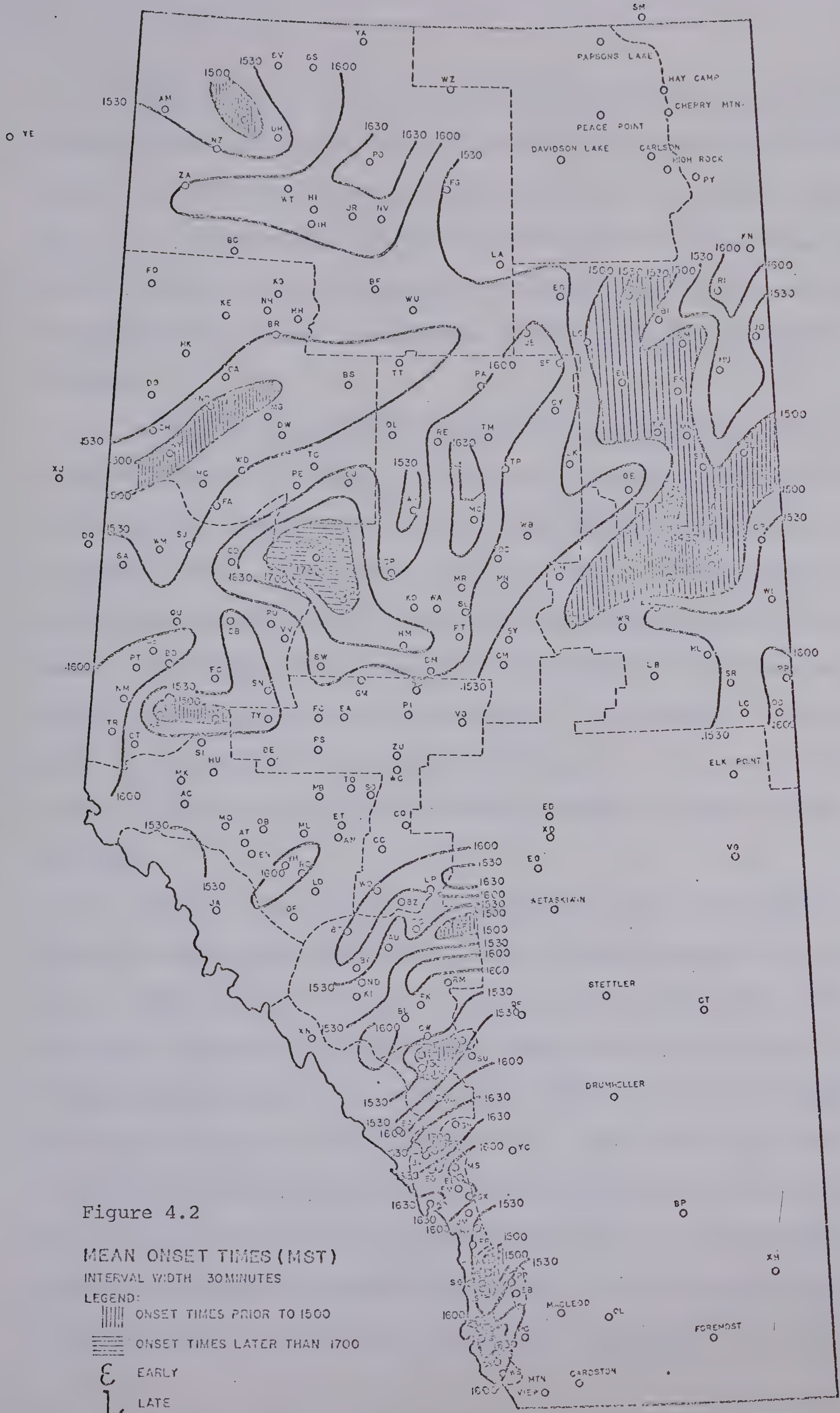

Figure 4.2

MEAN ONSET TIMES (MST)

INTERVAL WIDTH 30 MINUTES

LEGEND:

ONSET TIMES PRIOR TO 1500

ONSET TIMES LATER THAN 1700

E EARLY

L LATE

Figure 4.2, a map based on the Alberta Forest Service's lookout network points out the necessity of having a dense observational network if we desire to document the temporal variations of a mesoscale phenomena such as the thunderstorm. Comparison of Figures 4.1 and 4.2 demonstrates that the relative homogeneity found in the spatial distribution of mean occurrence times results from the sparse network of synoptic stations.

Graphs of the relative and cumulative frequencies of storm development similar to Figure C.1 (see Appendix C) were constructed for every synoptic station in Alberta for which Hourly Data Summaries were available. The stations in the northeastern part of the province show dual maxima occurring in the curves of hourly relative frequencies. In general, a maximum occurs between 1700 and 1800 MST with a secondary maximum occurring four to five hours later. For stations in the western parts of the province (see Appendix C) the relative frequency of thunderstorms gradually decreases after reaching a maximum between 1700 and 2000 MST.

Figure 4.2 is a plot of the mean onset times of all thunderstorms occurring within the visual range of Alberta Forest Service lookouts. The isochrones, drawn at 30 minute intervals demonstrate that, in the mean, thunderstorms commence three hours earlier at lookouts in the central Athabasca and Lac la Biche forests than they do in the southern Peace River and eastern Slave Lake forests. Early mean onset times characterize storm development at stations located on the southern slopes of the Clear Hills and at the Kakwa Lookout (KA). The organized patterns appearing on Figure 4.2 suggest that triggering mechanisms operating during the early afternoon must be partially responsible for the early

onset times observed in some areas. The singularities which develop in the isochrone pattern over the southern forest imply that storm development in the foothills is very localized.

In order to resolve the relationships between onset times and geographical features such as station elevation and station location, correlation coefficients were calculated employing the CCC technique. Appendix D, which lists the results of this analysis, indicates that storm development in the elevated forests can be correlated with neither station elevation nor station location. In the lowland forests the mean onset time at a particular station is positively correlated with the longitude of that station. The 0.3 correlation coefficient and the resultant t-score of 2.3 indicates that only 2.5 per cent of the time would such a correlation result from chance alone. This relationship suggests that topographical features in the eastern parts of the province are initiating thunderstorms earlier in the day.

A partial explanation for this correlation is found in the earth's rotation which causes the solar noon to occur 40 minutes later at 120°W than it does at 110°W. For a given latitude, a given time and uniform meteorological conditions more thermal energy would have accumulated in the boundary layer at a point in eastern Alberta than for a point in western Alberta. If we assume the effects of frontal activity in initiating thunderstorms to be random throughout the day, the correlation implies that for given instabilities, synoptic conditions and wind fields throughout the troposphere, a definite quantity of thermal energy must be accumulated in the boundary layer before thunderstorm development will occur.

The application of the AEH technique provides some insight into

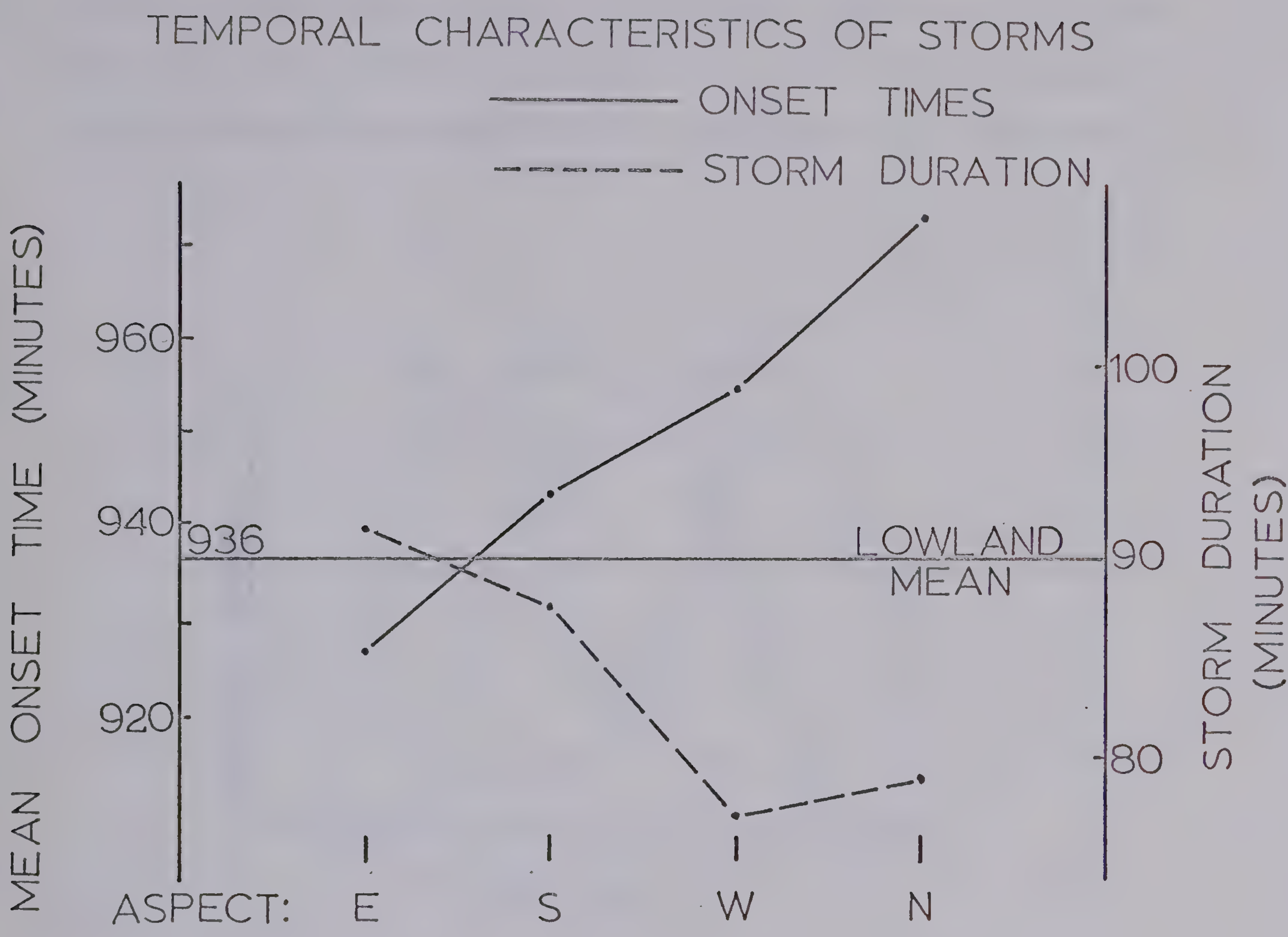

Figure 4.3 MEAN ONSET TIMES AND MEAN DURATION TIMES OF THUNDERSTORMS RELATED TO THE DIRECTION OF SLOPE AT THE OBSERVING SITE. The mean onset time in minutes after midnight (Mountain Standard Time) is given along the left-hand ordinate, e.g. 960 = 1600 MST. The horizontal line represents the mean onset time and the mean duration for thunderstorms in the lowland forests.

the governing physical laws. As Figure 4.3 indicates (and Appendix E enumerates) thunderstorms at stations located on east-facing slopes occur earlier than do storms occurring at lookouts on north-facing slopes. Starting on the eastern slopes, the mean onset times occur later as we

move clockwise around the hill. As is shown in Figure 4.4, the radiation absorbed by vertical east-facing walls is maximum in the morning. In the afternoon this maximum shifts to west-facing walls and slopes.

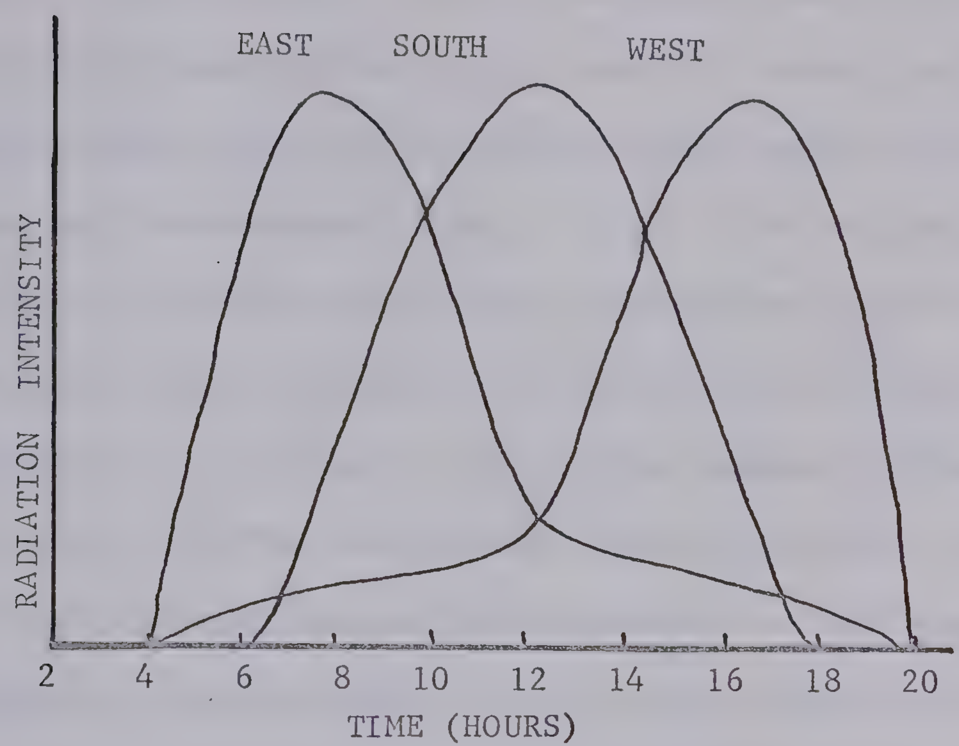

Figure 4.4 VARIATIONS IN THE INTENSITY OF RADIATION RECEIVED ON VERTICAL SURFACES WITH VARYING ASPECTS. (after Basset and Pritchard, 1969).

Although the weaker height gradients in the Clear and Swan Hills would diffuse these maxima, the eastern slopes would intercept much more of the morning heating than would the western slopes. The shape of the graphs follows naturally from direct proportionality existing between the intensity of radiation received on a surface and the sine of the sun's angle of elevation relative to that surface. The curve for the south-facing wall has been multiplied by a constant so its maximum would

be commensurate with the other two peaks.

On a clear day over a hill of uniform albedo we would conclude that maximum heating would occur on the eastern slopes in the morning. This maximum will be accompanied by large vertical transfers of heat and moisture, which not only produce cumulus congestus clouds but they modify the layer of free convection. As the day progresses this heating shifts to the southern slopes and then to the western slopes. On the basis of the foregoing deduction early afternoon cumulus growth would be expected on southern and southeastern slopes of hills. The mean onset time of 1520 MST for all thunderstorms forming at stations located on east-facing slopes confirms that the growth of thunderclouds over eastern slopes will occur earlier in the day. These storms appear to form from the thermals present over the southwestern slopes during the early afternoon. As these clouds migrate eastward they pass into an environment which has been modified to the point where it will tend to assist their growth. The copious heat and moisture supply provided to the cloud as it traverses the southern slopes enables it to grow into the mature cumulonimbus stage by the mid-afternoon when it reaches the eastern slopes.

Although this discussion has neglected the effects of the wind field, wind does play a significant part in transferring heat and moisture from the layers of forced convection to the layers of free convection. Wind often assists convection by liberating buoyant bubbles trapped in the boundary layer. As Braham and Draginis (1960) point out, the relative importance of the "barrier" effect and the "high level heat source" effect is little known and requires further investigation.

The ALR technique was applied to mean onset times in order to see how the onset times were affected by the presence of the Rocky

Mountains. Figure 4.5 shows the variations in onset times in the lee of the Continental Divide. Immediately to the east of the Divide storms are first seen, on the average, at 1540 MST. Farther to the east, in zone 3, cumulonimbus clouds produce lightning (or thunder) 20 to 25 minutes earlier in the afternoon. The delay in onset times in zones 4 and 5 suggests that the storms forming in zones 3 and 4 move eastward into zone 5.

The daily variations in onset times throughout the season were found by averaging the onset times of storms for each day. Figure 4.6 gives the resultant time series after the mean for the series was extracted. The first day corresponds to May 16 with the series extending until September 7, 115 days later. The high-frequency variations, indicating large variations in the mean onset times from one day to the next, constitute the most significant feature on this graph. The trend towards later onset times near the end of the season, masked by the high-frequency component on this graph can be seen in Figure 4.7.

In Figure 4.7, the high-frequency variations have been filtered out by passing the original time series through a symmetrical, triangular filter seven days in length. The resultant series, which has been terminated on the third of September, shows a trend for later onset times after August 20th. The trough present in the series near June 14 suggests that earlier onset times occur during the longer days in June. If we postulate that a definite quantity of radiation must be absorbed at the earth's surface before thunderstorms will occur, it then follows that under similar conditions in the troposphere June thunderstorms will develop earlier in the day than will September thunderstorms. The return to later onset times around June 29 is accompanied by a southward

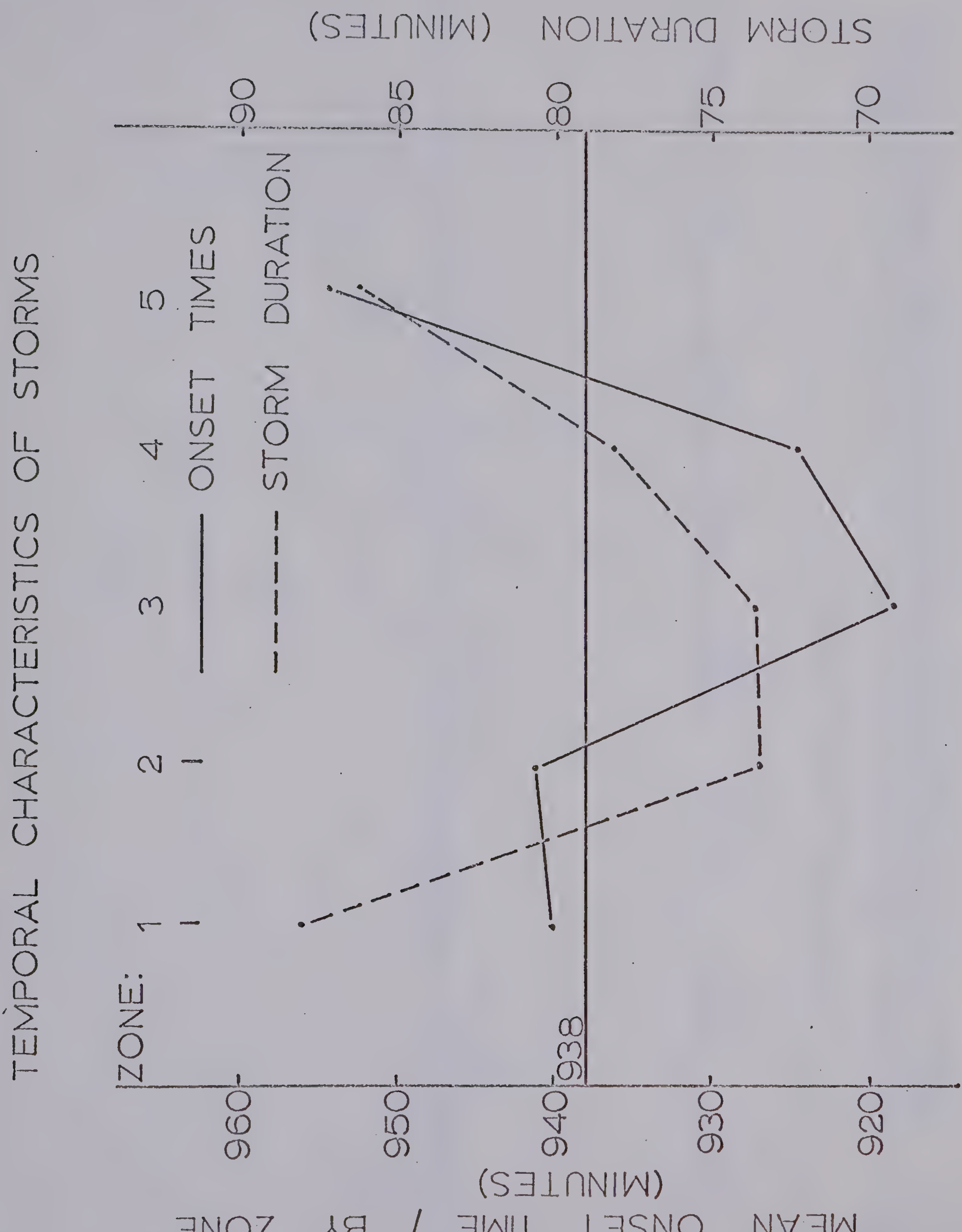

Figure 4.5 MEAN ONSET TIMES AND MEAN THUNDERSTORM DURATIONS IN THE LEE OF THE CONTINENTAL DIVIDE. The onset times are given in minutes past midnight (MST), e.g. 960 = 1600 MST.

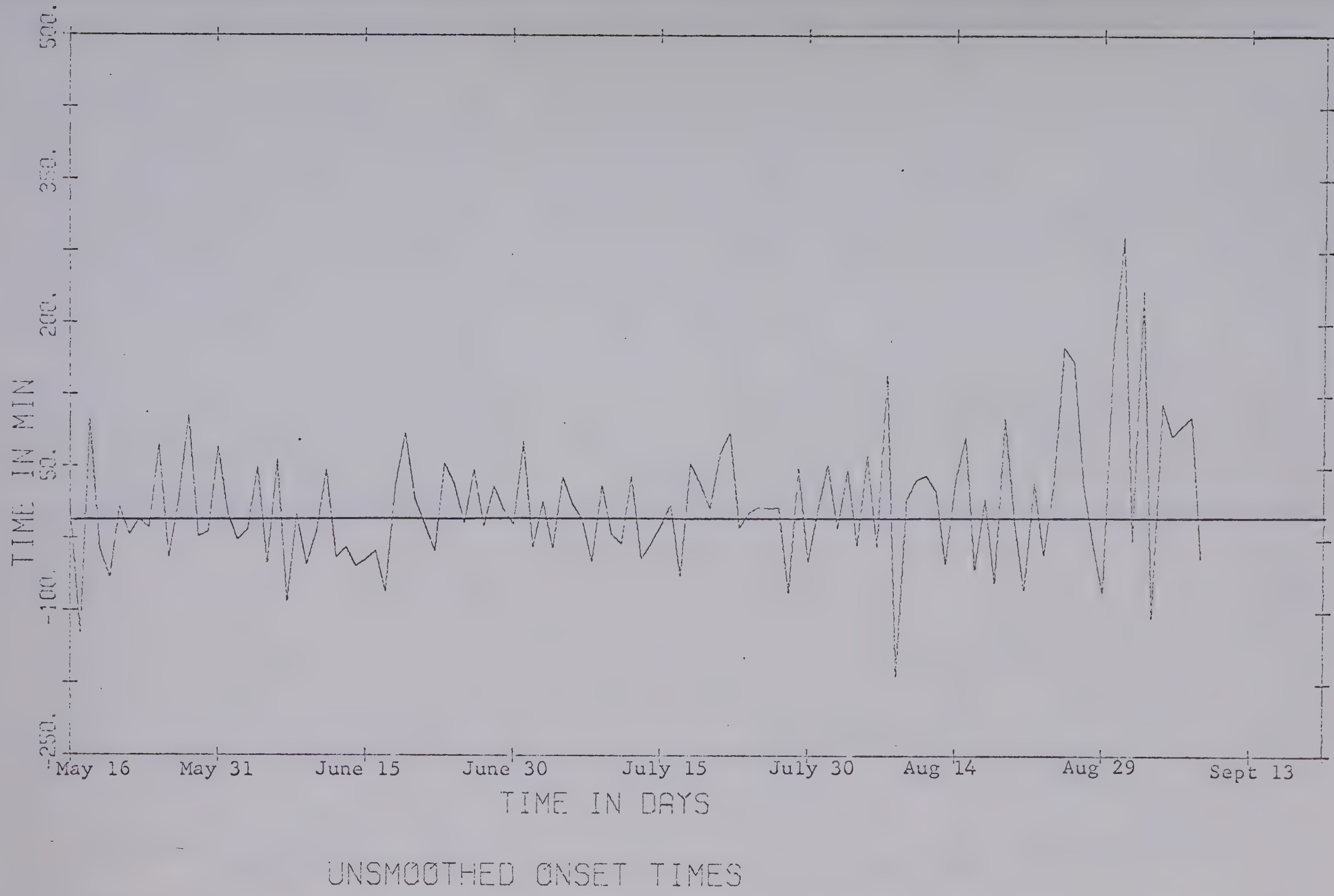

Figure 4.6 VARIATIONS IN THE UNSMOOTHED DISTRIBUTION OF MEAN DAILY ONSET TIMES FROM THE SEASONAL MEAN. The seasonal mean shown by the horizontal line is 15 hours and 30 minutes past midnight. The plot commences on May 7 and concludes September 7.

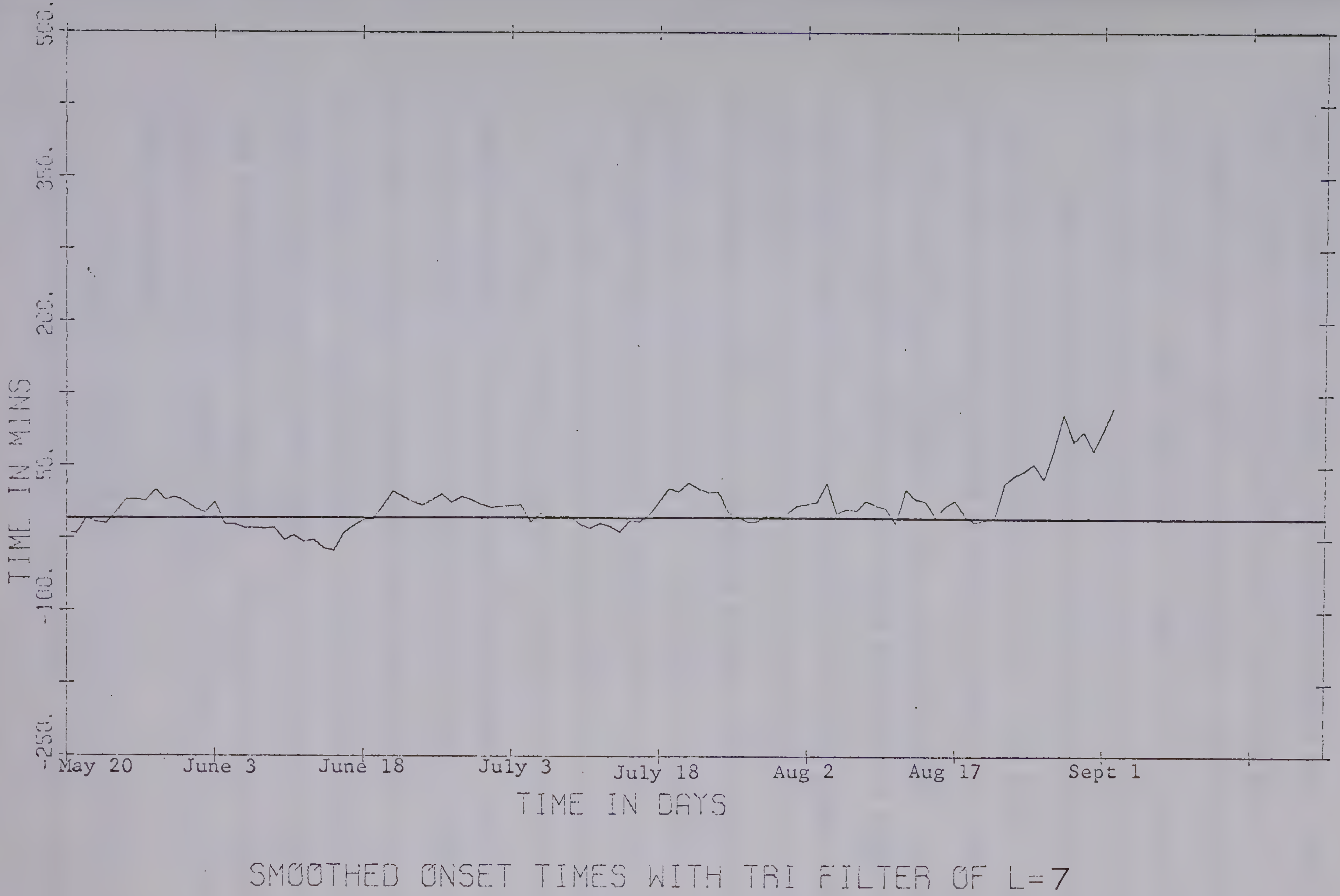

Figure 4.7 VARIATIONS IN THE SMOOTHED DISTRIBUTIONS OF MEAN DAILY ONSET TIMES FROM THE SEASONAL MEAN. The horizontal line represents the seasonal mean of 1530 MST. The plot continues from May 20 to September 3.

shift in thunderstorm activity. The interval between June 15 and June 20 was sampled, as was the interval between July 10 and July 15. In the June sample 26 thunderstorms were found between 58 and 60 degrees north, 15 per cent of the number being present between 53 and 55 degrees north. For the interval in July this proportion had decreased to 9.5 per cent.

Table 4.1 lists the values of the autocorrelation functions obtained from both the original and smoothed series. The negative autocorrelation coefficient shows the effects of the daily variations on the structure of the time series. Both the autocorrelation coefficient for a one-day lag and the variations evident in Figure 4.6 suggest that early onset times on one day are followed by late onset times on the subsequent day. In the later parts of the season where fewer reports are available for analysis the amplitudes of these daily variations increase. This increase combined with the absence of any obvious physical reason for the variations suggests that the noise present in the time series is the manifestation of an obscure bias in the data.

In order to obtain an evaluation of the significance of the onset-time spectra, two individual years were examined. Figures 4.8 and 4.9 display the onset times of thunderstorms in 1966 and 1968 respectively. Both years indicate early onset times near June 20 just as the spectrum for all years indicated. A definite minimum appears on Figure 4.8 near August 19 which appears as a minor trough on the filtered series displayed in Figure 4.7. The physical cause for this decrease is not evident nor does it appear as significant as does the trough on June 20.

The large variations from day to day provide some insight into the effects of synoptic processes on onset times. In order to make the

TABLE 4.1

AUTOCORRELATION COEFFICIENTS FOR SMOOTHED AND UNSMOOTHED ONSET TIMES

TIME LAG (DAYS)	r FOR UNSMOOTHED ONSET TIMES FOR ALL YEARS	r SMOOTHED ONSET TIMES FOR ALL YEARS	r SMOOTHED ONSET TIMES FOR 1966	r SMOOTHED ONSET TIMES FOR 1968
0	1.00	1.00	1.00	1.00
1	- .32	.47	.23	.50
2	.10	.38	.09	.00
3	.03	.06	- .05	- .11
4	.06	.19	- .04	- .08
5	.01	.06	- .01	- .09
6	- .06	- .07	- .03	- .12
7	.11	- .07	- .02	- .14
8	- .27	- .06	.06	- .10
9	.08	- .09	.12	- .08

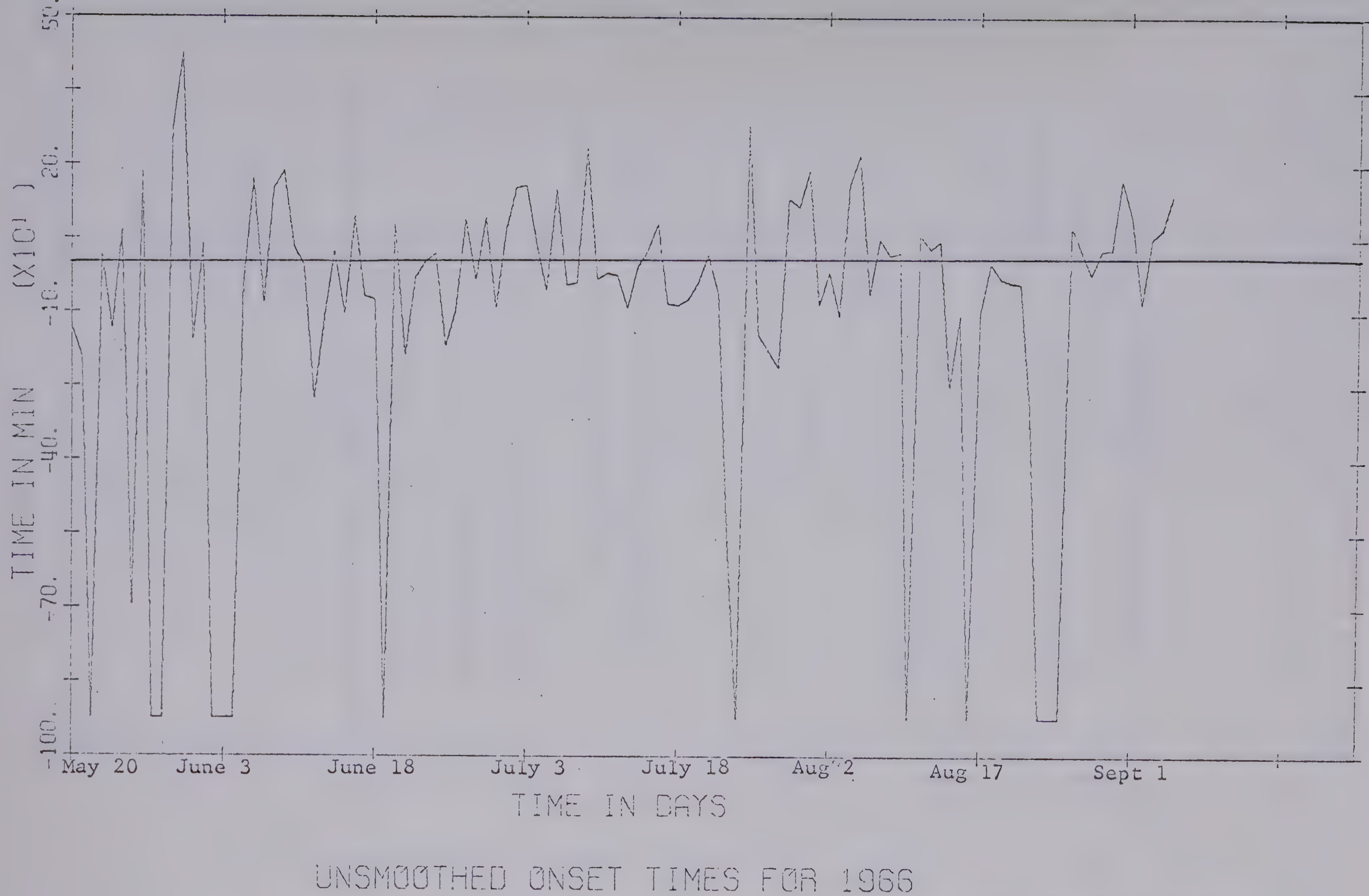

Figure 4.8 VARIATIONS IN THE UNSMOOTHED DISTRIBUTION OF MEAN DAILY ONSET TIMES IN 1966 FROM THE 1966 SEASONAL MEAN. The horizontal line represents the seasonal mean of 1544 MST. The spectrum commences on May 20 and terminates on September 6.

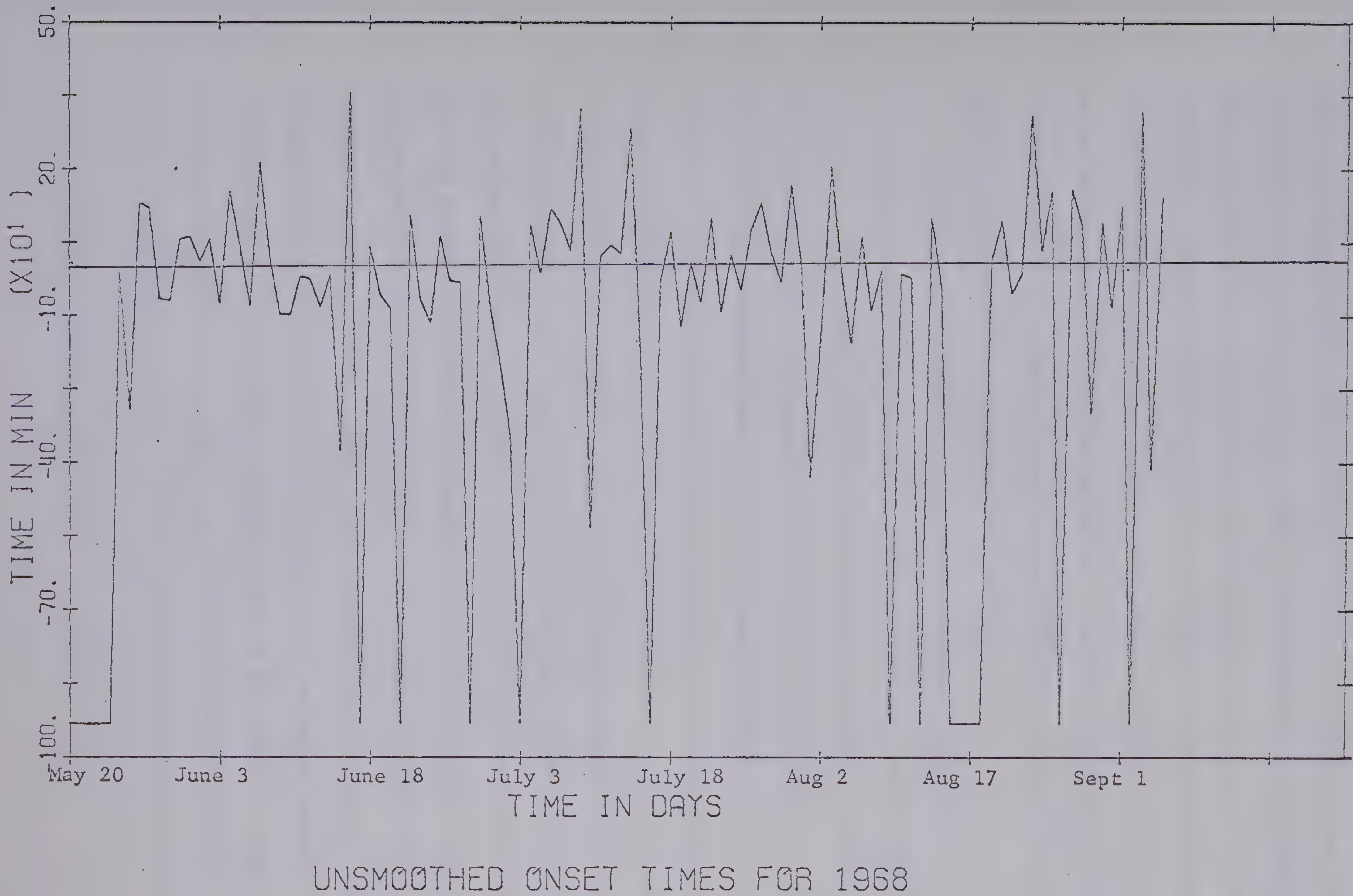

Figure 4.9 VARIATIONS IN THE UNSMOOTHED DISTRIBUTION OF MEAN DAILY ONSET TIMES IN 1968 FROM THE 1968 SEASONAL MEAN. The horizontal line represents the seasonal mean of 1546 MST. The graph continues from May 20 to September 8.

graphs more meaningful, both spectra were passed through a symmetric triangular lag window of 7 days width. The autocorrelation coefficients obtained from these filtered spectra are given on Table 4.1. It was found that even the filtered spectra had autocorrelation coefficients which decreased to zero in 2 days in 1968 and in 3 days in 1966. The rapid attenuation of the autocorrelation function with lags slightly greater than zero reflects the effects of 500-mb troughs and other synoptic features which pass through the province.

The spatial distribution of the cumulative frequencies of thunderstorm onset times were also examined, and maps are included in a report to the Alberta Forest Service (Lawford, 1970b). Five per cent of the storms in the northern Lac la Biche Forest and 2.5 - 15.5 per cent of the thunderstorms in the Crowsnest Forest occur prior to 0600 MST. The activity occurring at the mountain stations during the early morning was attributed to the influence of the Rocky Mountains. In the northeastern parts of the province the early morning secondary maximum suggests that a mechanism other than surface heating must be initiating convectional activity. This nocturnal maximum shown for eastern Alberta in Appendix C appears to become increasingly significant east of the Continental Divide as the 2200 CST maximum at Winnipeg implies (Lipson, 1965). The appearance of nocturnal storms several hundred miles to the east of the Rocky Mountains suggests that a characteristic flow pattern forming over the provinces of Saskatchewan and Manitoba during the summer months frequently triggers instability during the night. Another map[1] which shows the relative

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1 not shown in this dissertation.

frequencies of thunderstorms commencing between 1200 and 1500 LST, indicates that early afternoon thunderstorms tend to occur over south-eastern slopes and at individual lookouts along the foothills.

4.3 DURATIONS OF THUNDERSTORMS

The length of time that a thunderstorm persists is of economical interest as well as being a fundamental statistic in the understanding of Alberta thunderstorms. In this analysis the life of a thunderstorm was taken as the time differential between the last manifestation of the thunderstorm's existence and the onset times of the same storm. Storm durations are affected by several factors. Consequently the length of time spent by a storm in the vicinity of a particular station must provide some insight into the mechanics of thunderstorm development at that station.

Thunderstorm duration is a function of:

1) the degree of modification the layer of free convection has undergone. In a highly destabilized atmosphere thunderstorm growth will be accentuated and as a result a thundercloud, once formed, will tend to persist.

2) the location of the cumulonimbus when it reveals its identity. Clouds evolving into thunderclouds to the east of a reporting station will move out of the observer's field of view shortly after they are recognized. A thunderstorm forming to the west of a particular station in a westerly air flow may complete its life cycle within the view of an observer as it passes from west to east.

3) the stage of the storm's development when it is initially observed. Disregarding the influences of environmental

modification, thunderstorms forming in view of a specific lookout will be observed longer than those storms which first become visible after they have reached the dissipative stages. On the other hand, duration times could be used to establish the spatial distribution of thunderstorm development.

In order to establish which factors are responsible for the patterns present in the distribution of thunderstorm persistences, the relationships between duration times and other factors must be known.

Byers and Braham (1949) postulated that single-celled thunderstorms have forty-minute life-cycles. Figure 4.10, a map indicating the mean duration times of thunderstorms occurring over Alberta forests, shows that longer-than-usual duration times characterize Alberta thunderstorms. The frequent mean durations exceeding 100 minutes suggests that many, if not most, of Alberta's thunderstorms are either multicellular or in a quasi-steady state at some stage of their life-cycle.

Storm durations are related to the elevation of the station at which the thunderstorm forms. Over elevated forests, storm durations are related to elevation and latitude by correlation coefficients of -0.27 and 0.27 respectively. The negative correlation between station elevation and storm duration exists in spite of observational bias which influences the results. The observer at a higher lookout can survey a larger area and should be able to view the storm for a longer period of time.

These correlations may also be reflecting the modifying effects of mountain waves on thunderstorms. The short duration times of mountain thunderstorms, indicated by the negative correlation between

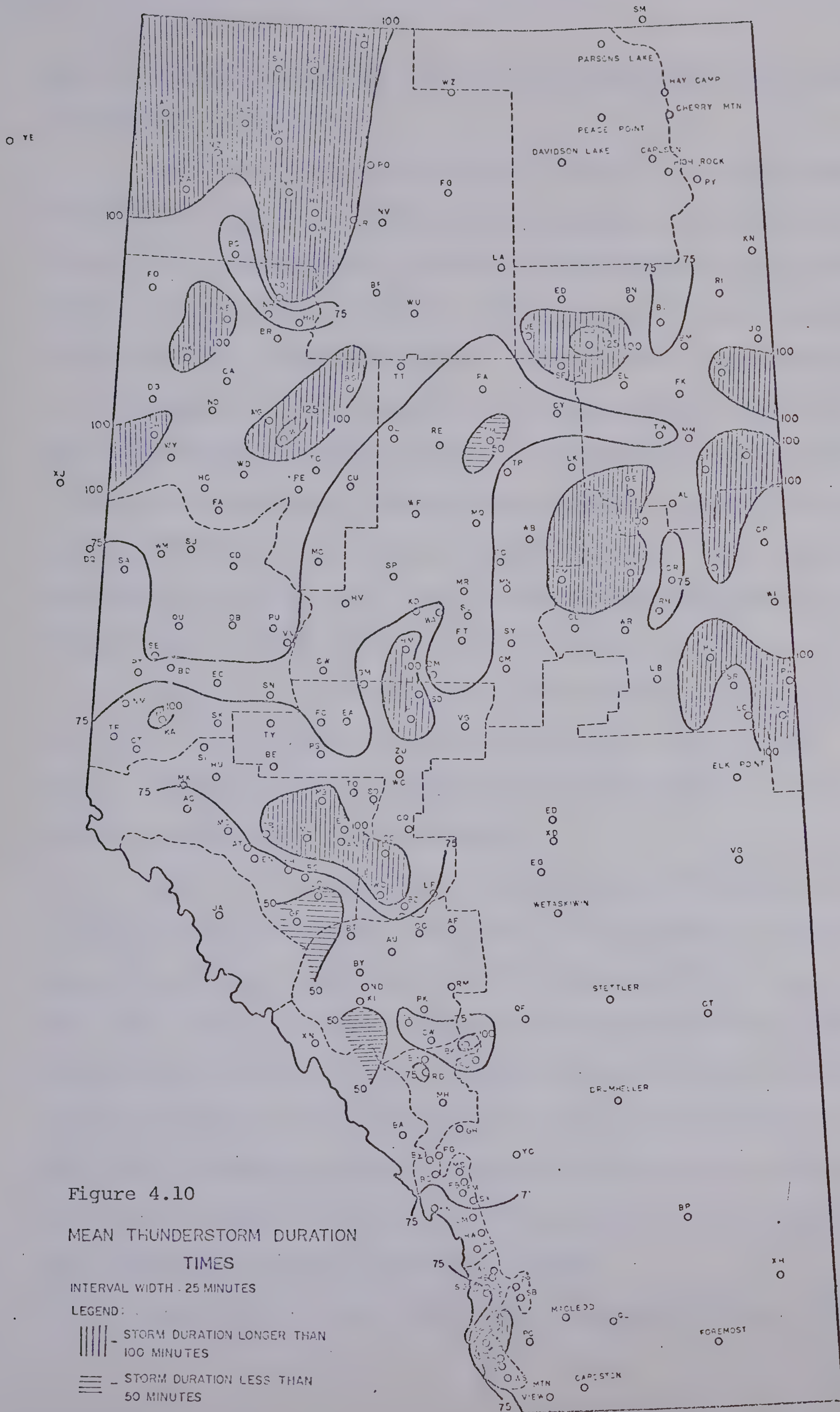

Figure 4.10

MEAN THUNDERSTORM DURATION TIMES

INTERVAL WIDTH - 25 MINUTES

LEGEND:

- STORM DURATION LONGER THAN 100 MINUTES

- STORM DURATION LESS THAN 50 MINUTES

elevation and storm duration result from lee waves which lead to rapid thunderstorm dissipation.

The ALR technique was applied to investigate the effect the Continental Divide has on storm durations. Figure 4.5 shows that in zones 2 and 3 thunderstorms are relatively short while storms in zone 5 persist, on the average, 8 minutes longer than the 78 minute mean duration present in the elevated forests. The rapid decrease in storm duration between zones 1 and 2 suggests that some mechanism, possibly the subsidence associated with a mesoscale wave phenomenon, is preventing thunderstorm propagation. The short mean duration in zone 3, the zone where onset times suggest that a transformation from cumulus to mature cumulonimbus is taking place, seem to indicate thunderstorms first discharge cloud-to-ground lightning east of the stations of this zone.

Dirks et al (1967) postulate a mesoscale wave phenomena to exist under conditions of low stability and weak vertical wind shear. The development of thunderstorms in zone 3 appears to be the affect of similar phenomena in Alberta.

Over the lowland forests, latitude and storm durations were related with a 0.36 correlation coefficient. This tendency for storms to persist for longer time intervals in the northern parts of the province may result from the stronger influence of synoptic mechanisms in the northern part of the province. In cases where cold fronts or mid-tropospheric troughs are either initiating or propagating the development, the storm is usually moving with the generating mechanism. Because the moving source can provide the storm with a continuous supply of energy, the thunderstorm persists for a longer period.

Topographical features affect mean thunderstorm duration times.

This fact is borne out by the -0.42 correlation coefficient relating onset times and thunderstorm durations over lowland forests. This correlation, which states that early thunderstorms endure for longer periods, suggests that those areas in which the atmosphere is sufficiently modified by morning heat and moisture fluxes to give rise to early afternoon thunderstorms are also areas where atmospheric modification leads to longer thunderstorm durations.

Figure 4.3 shows the results obtained by applying the AEH technique to thunderstorm durations. The tendency for more durable storms on the eastern and southern slopes is the result of morning and early-afternoon heating. Because thunderstorms passing over these slopes are feeding on very buoyant air, they have stronger updrafts and endure longer than do storms travelling over western and northern slopes.

A second effect must be recognized. Thunderstorms which form over the eastern and southern slopes do so early in the afternoon. Consequently, thunderclouds observed on these slopes are in their early stages of development and may spend much time evolving through their life-cycle while in view of an observing station. By contrast a cumulonimbus observed on a western slope is likely to have moved in from some breeding ground farther to the west. As a result these storms will be in their late-mature or dissipative stages when first observed. Based on this approach we can hypothesize that the southern and southeastern slopes are areas of preferred thunderstorm development.

Figure 4.10 is a map showing the spatial distribution of mean thunderstorm durations. The pattern which results appears rather disorganized although a few interesting features can be noted. With the exception of a maximum in the southern Crowsnest Forest the

mountains are characterized by short storm durations. The strong gradients which exist in the Edson Forest suggest that the minimum storm durations are delineating areas of thunderstorm development. Similar highly localized isochronal gradients which exist elsewhere on the map reflect the effects of topography either on thunderstorm generation or thunderstorm translation.

Thunderstorms have a tendency to follow valleys or other terrain features which can sustain them by supplying the necessary heat and moisture. The intricate isochronal patterns present on Figure 4.10 result in part from the tendency to locate forestry lookouts at vantage points where they can survey certain valleys.

4.4 THE SEASONAL DISTRIBUTION OF THUNDERSTORMS

In analyzing the relative importance of certain geographical features in the development of thunderstorms, the time of the year must be considered. Seasonal variations are most pronounced in the northern latitudes. At 58°N the amount of short-wave radiation incident on the top of the earth's atmosphere drops by 45 per cent between June 15th and September 15th. To a large extent the solar zenith angle determines the micro-climate of an individual hill and the effect it will have on thunderstorm formation. The mean height and wind fields at all pressure levels undergo significant transitions with the passage of the seasons. As a result the wave phenomena occurring to the lee of the Rocky Mountain Range will have season-dependent effects on the structure of the meteorological fields within the layer of free convection.

The seasonal distribution of thunderstorm activity can be partially described by the date of the median thunderstorm day. A thunderstorm day is defined as any day on which one or more thunderstorms are

observed at the station under consideration. Over the elevated forests the median date was correlated to station elevation with a coefficient of 0.40. This correlation, significant at the 99 per cent confidence limits, suggests that late season storms tend to occur over higher terrain. Similarly storms over lowland forests had median dates related to elevation with a 0.41 correlation coefficient.

The dependence of late season storm development on elevation implies that high terrain can initiate thunderstorms late in the season while lower elevation sources are not so capable. The relative importance of elevation in thunderstorm generation increases as the amount of insolation received from the sun decreases. High altitude lookouts in the southern forests are often situated on rock and surrounded by very steep slopes. For a given synoptic situation the combined effects of albedo and increased heating over surfaces perpendicular to the sun's rays result in the accumulation of the quantity of energy required to initiate a thunderstorm. Over lower terrain where slope gradients are weaker, the energy accumulated on a late summer day is inadequate to produce the energetic thermals required for the formation of a thundercloud. The modification which occurs in the atmosphere overlying the lower terrain during the months of August and September will often be insufficient to allow the propagation of developed thunderstorms. Both processes are responsible for the observed correlation.

A highly significant correlation coefficient of -0.60 associates the date of the median thunderstorm day and the latitude of the lowland station observing the thunderstorms. This correlation, which demonstrates the late-season median thunderstorm day dates as we move southward, reflects the dependency of thunderstorm occurrence in the northern forests

on the season. The southward shift in thunderstorm activity, indicated by the relatively late-season median dates present over the more southerly lowland forests, appears to be concurrent with the rapid decrease in the short wave radiation received by the northern forests after mid-July. This shift suggests that, for a given set of meteorological fields in the upper atmosphere, a definite quantity of thermal energy must accumulate in the low levels before an air mass thunderstorm will form. Generalizing this deduction to include all types of thunderstorms the threshold energy hypothesis of thunderstorm development can be articulated. This generalization cited by Lawford (1970c) states that:

For a given meteorological structure in the overlying atmosphere, the kinetic energy possessed by either a rising parcel of air or a thermal in the layer of forced convection must reach some threshold value before thunderstorms will form.

Based on this generalization a threshold value of energy (thermal or kinetic) exists which must be exceeded before thunderstorms will form. This threshold value would vary from day to day. Low humidities, stable lapse rates and subsidence in the lower and mid-troposphere would all tend to increase the critical value. Those areas where either the kinetic energy of thermals on a cold front or the thermal energy of some climatic source region first exceed this threshold value localized the regions of thunderstorm development on a particular day. After the thunderstorm's formation, its intensity and duration will be determined by the structure of the meteorological fields in which the storm travels. This approach to thunderstorm forecasting provides a technique linking meteorological processes on several scales.

Over the elevated forests a feeble correlation exists between the data of the median thunderstorm and the onset time. The 0.26 coefficient implies that early season storms tend to occur earlier in the day. Applying the threshold energy hypothesis of thunderstorm development this correlation seems to be a natural consequence of the physical processes involved in the formation of air mass thunderstorms. During the month of June the long day-lengths permit the accumulation of critical energy values earlier in the day than do the shorter day-lengths of August and September. This trend for early storm development during the initial stages of the thunderstorm season is masked in Figure 4.7 because of the lack of a similar correlation in the northern forests and the latitudinal shifts in the centers of thunderstorm activity. This figure does show that daily mean onset times during May are later than similar values for mid-June, which supports the above conclusions regarding the affects of longer day lengths on the formation of air mass thunderstorms.

The median dates of thunderstorm day occurrences were plotted on a map and isochrones were constructed. The resultant map shown in Figure 4.11 shows a north-south gradient covering most of the province. As the CCC technique demonstrated, early median dates are found in the northern part of the province while late season medians predominate in the south. The role of insolation in the north is exemplified at Adair (AD) where one-half of the thunderstorm days occur prior to June 28th. The increased heat storage potential of the southern forests and the slower attenuation in the daily short-wave radiation totals over the southern forests account for the increase in the time lag between the median thunderstorm day date and the summer solstice. The late

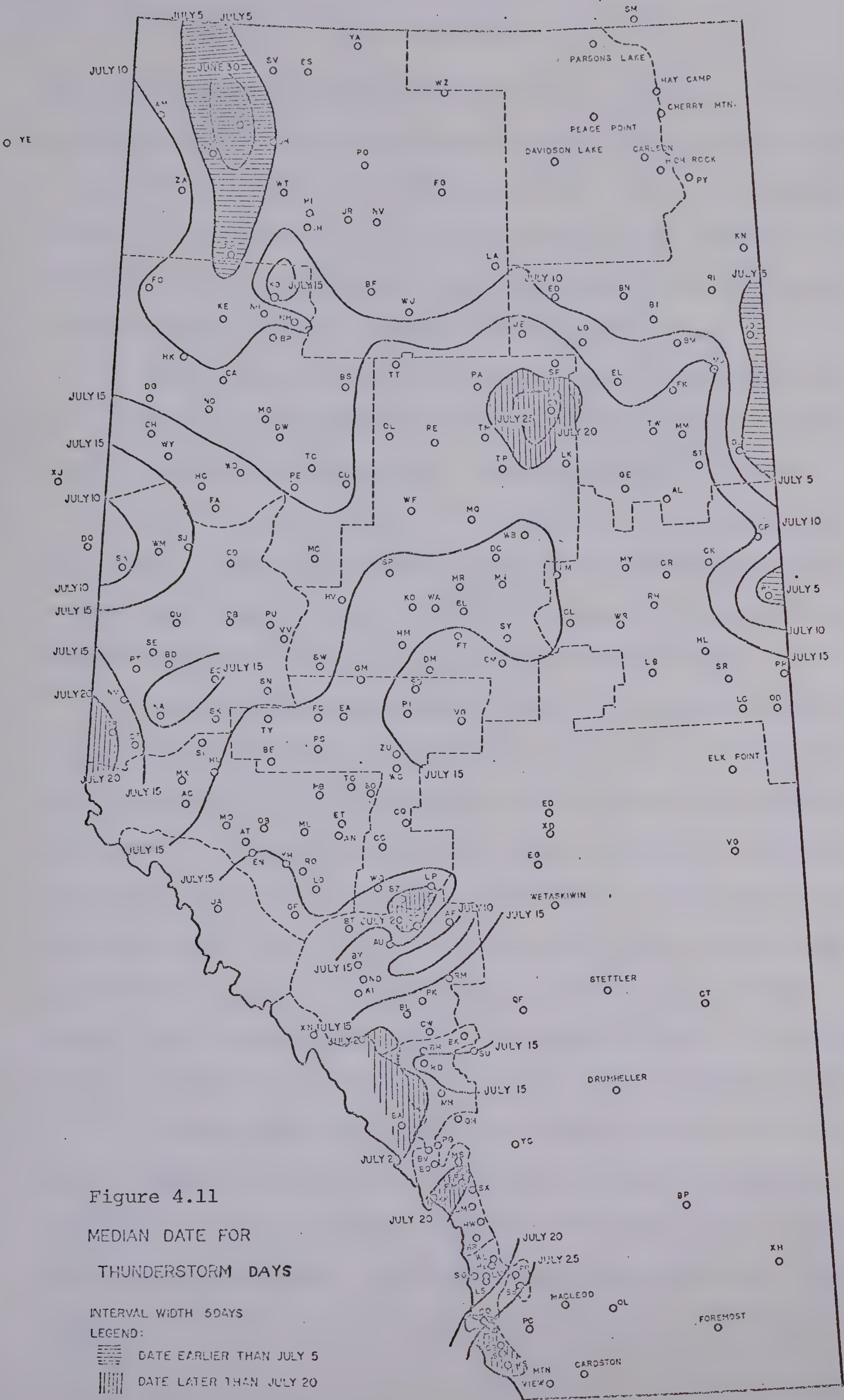

Figure 4.11

MEDIAN DATE FOR THUNDERSTORM DAYS

INTERVAL WIDTH 5DAYS

LEGEND:

DATE EARLIER THAN JULY 5

DATE LATER THAN JULY 20

median date at Chipewyan Lakes (CY) is an isolated anomaly in the pattern and appears to be the result of either a lookout which has been irregularly staffed or the effects of the nearby lake. The strong gradient present in the isopleths on the eastern fringes of the province may be the reflection of the climatic control responsible for the evolution of the secondary nocturnal thunderstorm frequency maximum.

Application of the ALR technique to median thunderstorm day dates indicated that the existence of a mesoscale wave phenomenon has little effect on the median dates. Although the time lag was only 40 per cent of the mean standard deviation present in the individual zones, later median dates were the result of the elevation-median date relationship, implying that the effects of elevated heat sources are responsible for the formation of late season thunderstorms.

Another necessary parameter of value to the practical forester or forecaster can be derived by calculating the relative frequency or empirical probability of the occurrence of a thunderstorm day during a given month. The following maps were derived by dividing the frequency of thunderstorm days at a particular station for a given month by the number of days in the month. After these values were plotted on maps, isopleths were constructed. The numerical values on maps are most readily interpreted by recognizing that a probability of 0.1 corresponds to the situation where three days each month will be thunderstorm days.

If thunderstorm development were completely random, as it would be if irregular synoptic scale processes were the sole triggering mechanism, then these patterns would fail to delineate areas of preferred storm development. All of the figures from 4.12 to 4.14 demonstrate the existence of areas of preferred development. These patterns

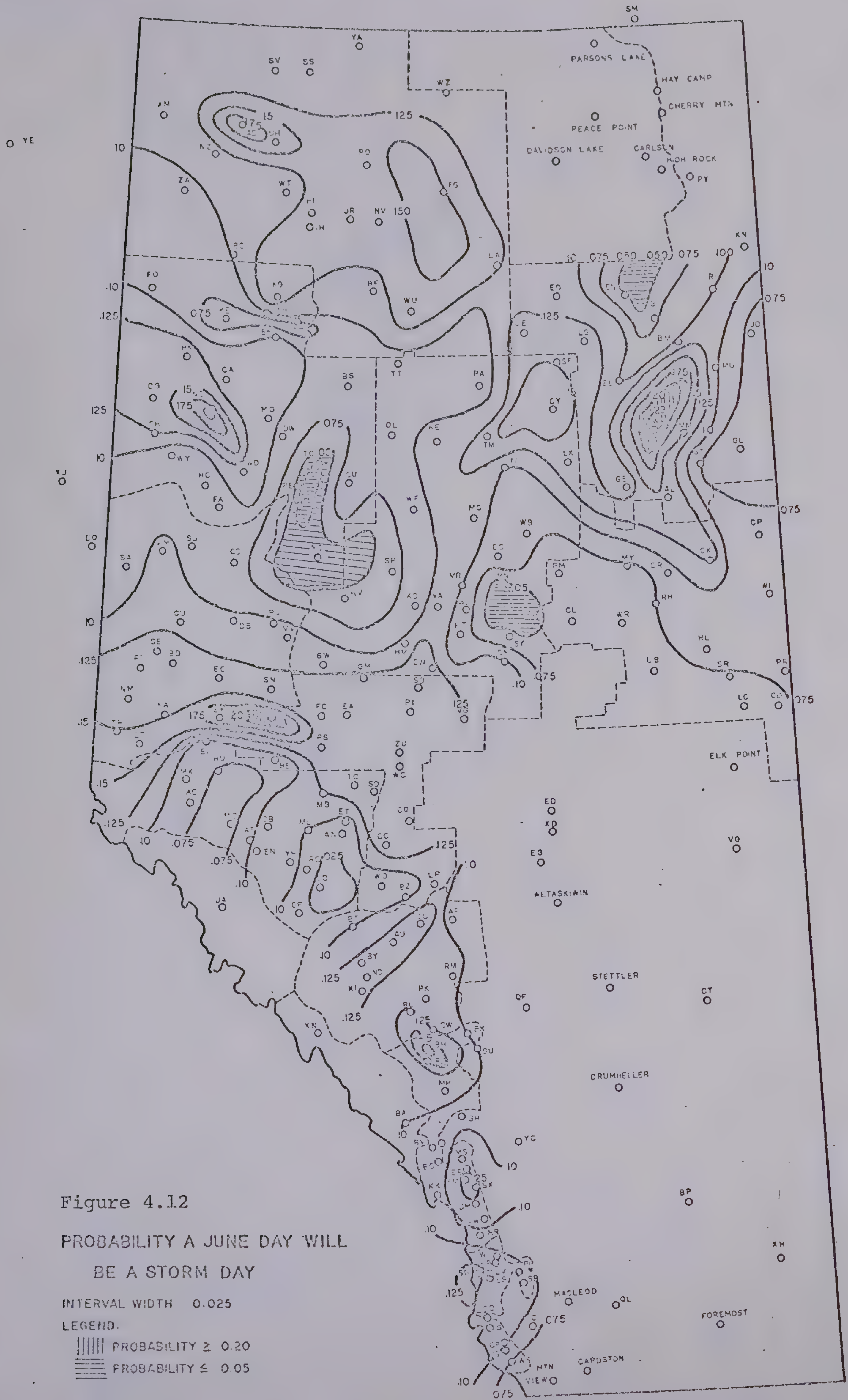

Figure 4.12

PROBABILITY A JUNE DAY WILL BE A STORM DAY

INTERVAL WIDTH 0.025

LEGEND.

||||| PROBABILITY ≥ 0.20

≡≡≡ PROBABILITY ≤ 0.05

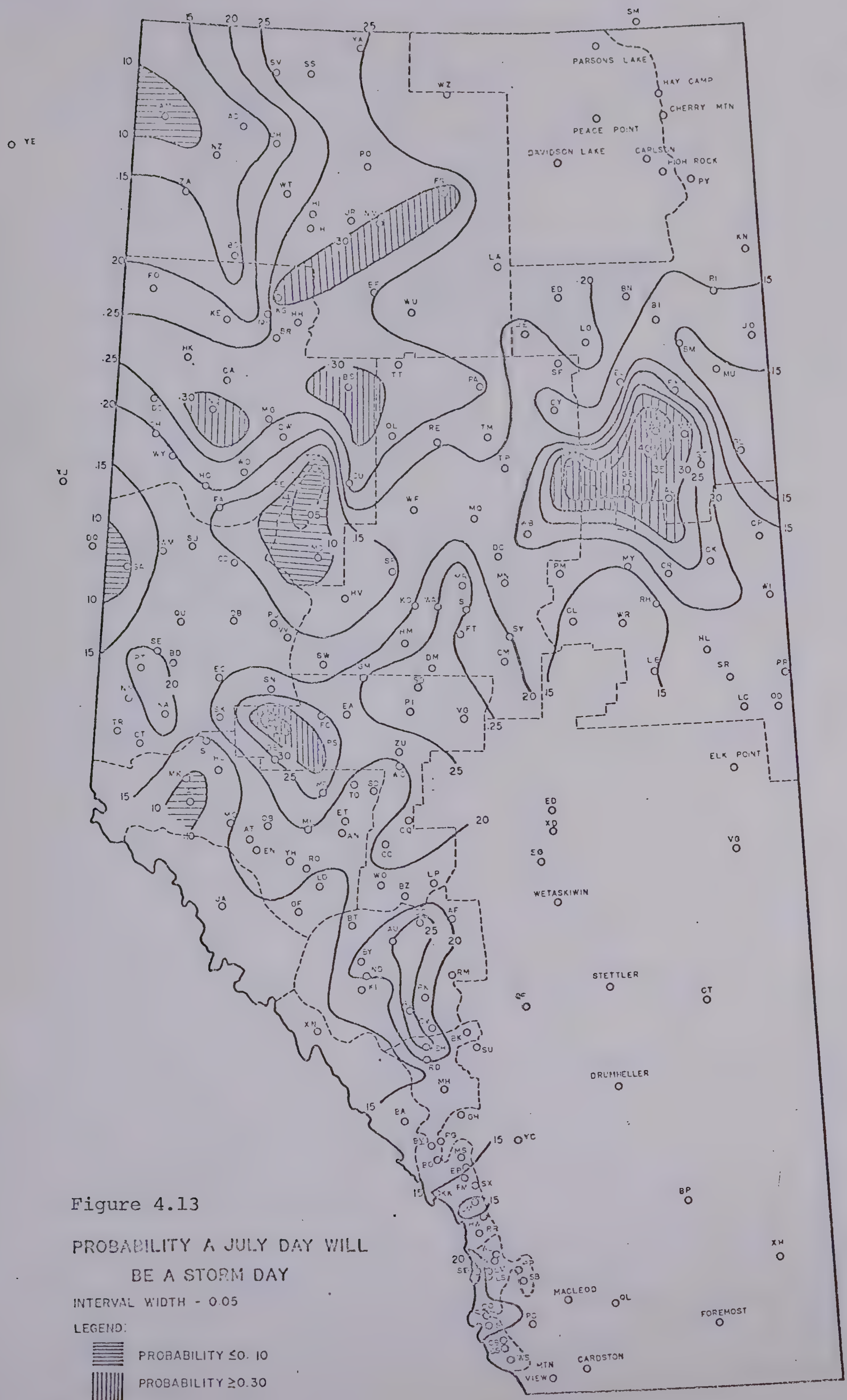

Figure 4.13

PROBABILITY A JULY DAY WILL BE A STORM DAY

INTERVAL WIDTH - 0.05

LEGEND:

PROBABILITY ≤0. 10

PROBABILITY ≥0.30

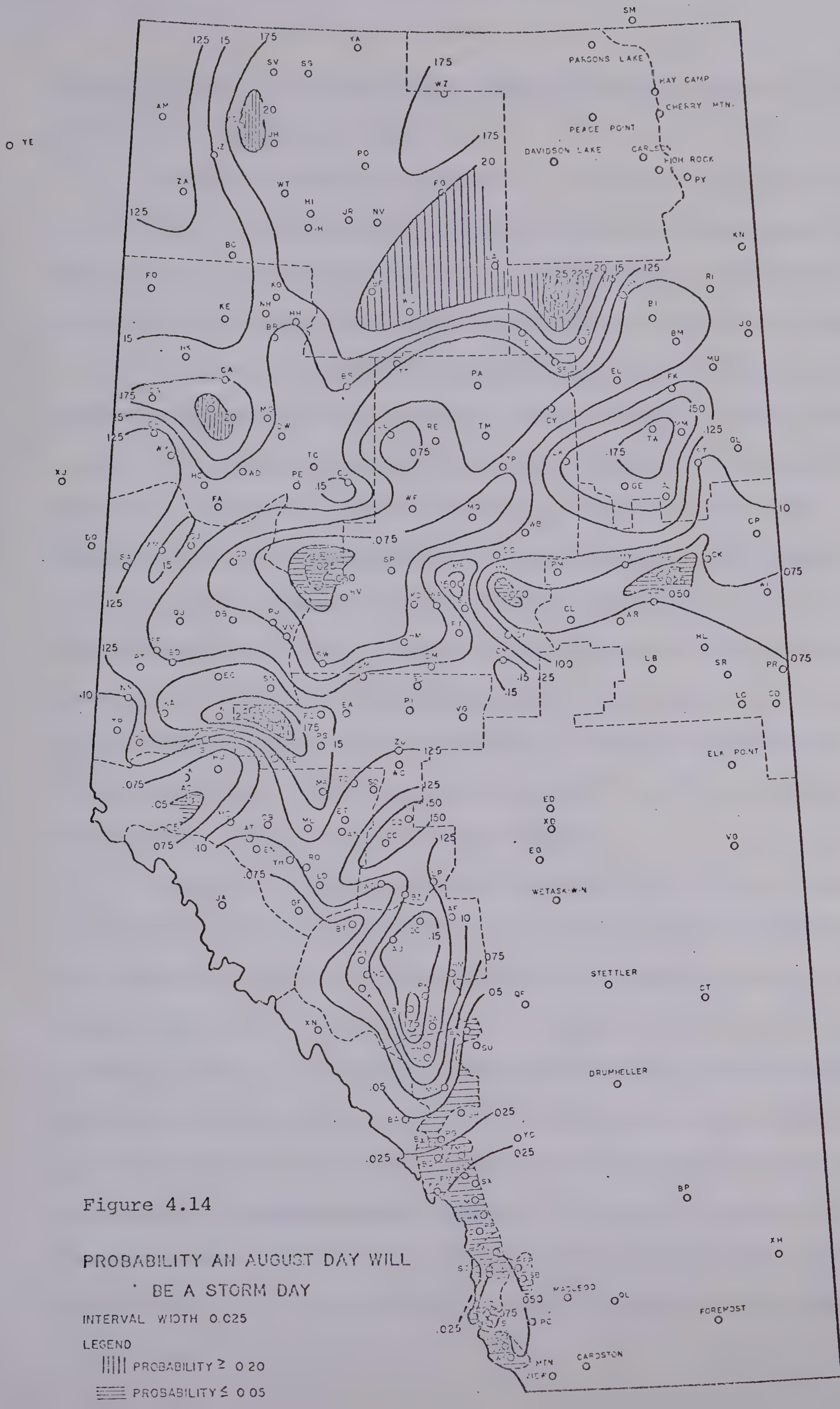

Figure 4.14

PROBABILITY AN AUGUST DAY WILL BE A STORM DAY

INTERVAL WIDTH 0.025

LEGEND

PROBABILITY ≥ 0.20

PROBABILITY ≤ 0.05

undergo changes from month to month, demonstrating the effects of the season on thunderstorm generation.

Figure 4.12 shows the frequencies of thunderstorm days for the month of June. A maximum appears in the vicinity of the Thickwood Lookout (TW) with a central value of 0.23. The activity in the Southern Athabasca Forest appears to be associated with the sloping valley walls of the Athabasca River and the slopes present in the Thickwood Hills. Another maximum appears on the eastern slopes of the Clear Hills while a maximum which had been centered at the Smoky Lookout (SK) during May shifts into the western extremities of the Whitecourt Forest. The southern forests are characterized by isolated minima. This suggests that during June orographic effects inhibit thunderstorm development. The elongated minima in the southern Peace River Forest which stretches along the Peace River valley appears to be the result of a lack of some topographical feature capable of triggering cumulonimbus development. It is also possible that wave phenomena to the lee of the Continental Divide may be suppressing thunderstorm activity.

In July, as Figure 4.13 shows, the probability of a day being a thunderstorm day reaches a maximum. The relative maximum occurring in the southern Athabasca Forest increases in both area and intensity. The central value of 0.45 at Thickwood (TW) implies that every second day is a thunderstorm day. The western Whitecourt maximum is oriented along a northwest-southeast axis and causes the isolines to be aligned parallel to the Continental Divide. This east-west gradient points up the effects of orography on thunderstorm development. The southern forests are characterized by relatively low probabilities as are the stations immediately to the east of the Divide. The strong minimum in the southern

Peace River Forest persists but thunderstorm development is frequent to the north on the southern slopes of the Buffalo Head Hills.

Figure 4.14, which is a plot of the August thunderstorm day probabilities, shows a broad minimum oriented in a northeast-southwest direction through the southern Peace River and central Slave Lake Forests. Although a weak maximum still exists in the southern Athabasca Forest the eastern forests are the scene of limited convective activity during August. Similar to the effects found in the elevated forests earlier, the mean early onset times were the result of early season storm development. The availability of early afternoon insolation during June and July means that storms during these months occur earlier in the day.

A new maximum evolves in August on the southeastern slopes of the Birch Mountains. This maximum along with the relative maximum present over the southeastern slopes of the Clear Hills implies that only the southern and southeastern slopes absorb sufficient thermal energy to generate air mass thunderstorms. The absorption of insolation by southern slopes appears to be the most effective storm development mechanism operating in northern Alberta forests during August. The other maxima in the western Whitecourt and southern Clearwater-Rocky Forests have more subtle topographic dependencies than do the northern maxima.

Thunderstorm probabilities are almost negligibly small during September. For the province as a whole, the pattern is similar to that found in August. The Tony (TY) maximum appears to have shifted northward to the western slopes of the Swan Hills reflecting the operation of a similar process to that present over the Birch Mountains. Over the Birch Mountains the activity during September has shifted from the southern to the western slopes.

During the months of June and July thunderstorms formed from the thermals present over the southern and southeastern slopes utilized most of the energy the atmosphere has stored while being modified from below by morning and early afternoon heat and moisture fluxes. As a result the thermals over the southwestern slopes which form during the late afternoon and early evening penetrated a stabilized environment where they could not initiate thunderstorms. In September, when modification must continue much later into the afternoon before threshold values are reached, only the southern slopes produce sufficiently energetic late afternoon thermals to initiate thunderclouds. This explanation is also supported by the late onset times characterizing late season thunderstorms (see Figure 4.7).

The maximum present in the Crowsnest forest emphasizes the major role elevated heat sources are playing in the production of September thunderstorms. In order to localize the effects of orography and topography as heat sources both the ALR and AEH techniques were applied to the thunderstorm day probabilities. Figure 4.15 displays the results obtained from applying the ALR technique.

With the exception of September, the ALR technique shows that the most frequent thunderstorm activity occurs in zones 4 and 5. During May, June and July the probabilities of thunderstorm days increase as we progress eastward from the Continental Divide. During these months the mesoscale wave mentioned earlier appears to be suppressing thunderstorm development in zones 1 and 2. During August when the probability of a thunderstorm day in zone 2 exceeds the probability in zone 3 the effects of elevated heat sources appears to dominate. This trend continues into September when the highest probabilities appear in zones 1 and 2.

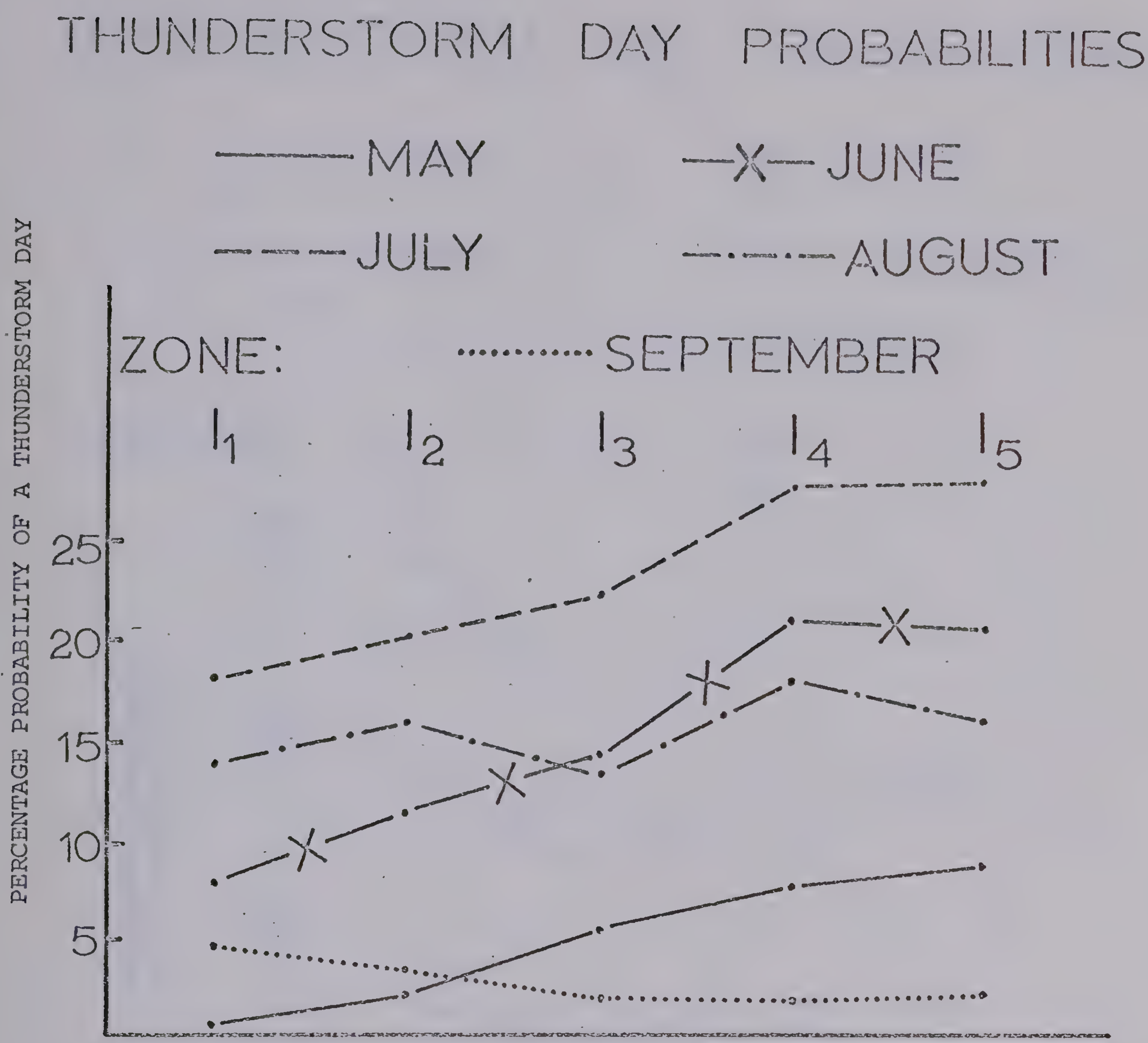

Figure 4.15 MONTHLY PROBABILITIES OF THUNDERSTORM DAYS IN THE LEE OF THE CONTINENTAL DIVIDE.

Figure 4.16 gives the results of the AEH analysis. Although the absolute magnitude of the differences observed between the various slopes is less than one mean standard deviation in all but one case, the seasonal trends are of interest.

The trend for maximum thunderstorm probabilities during July appears on Figure 4.16. During May, June and July thunderstorm activity is a minimum over southern slopes and a relative maximum on eastern slopes. During August this trend is reversed with maximum

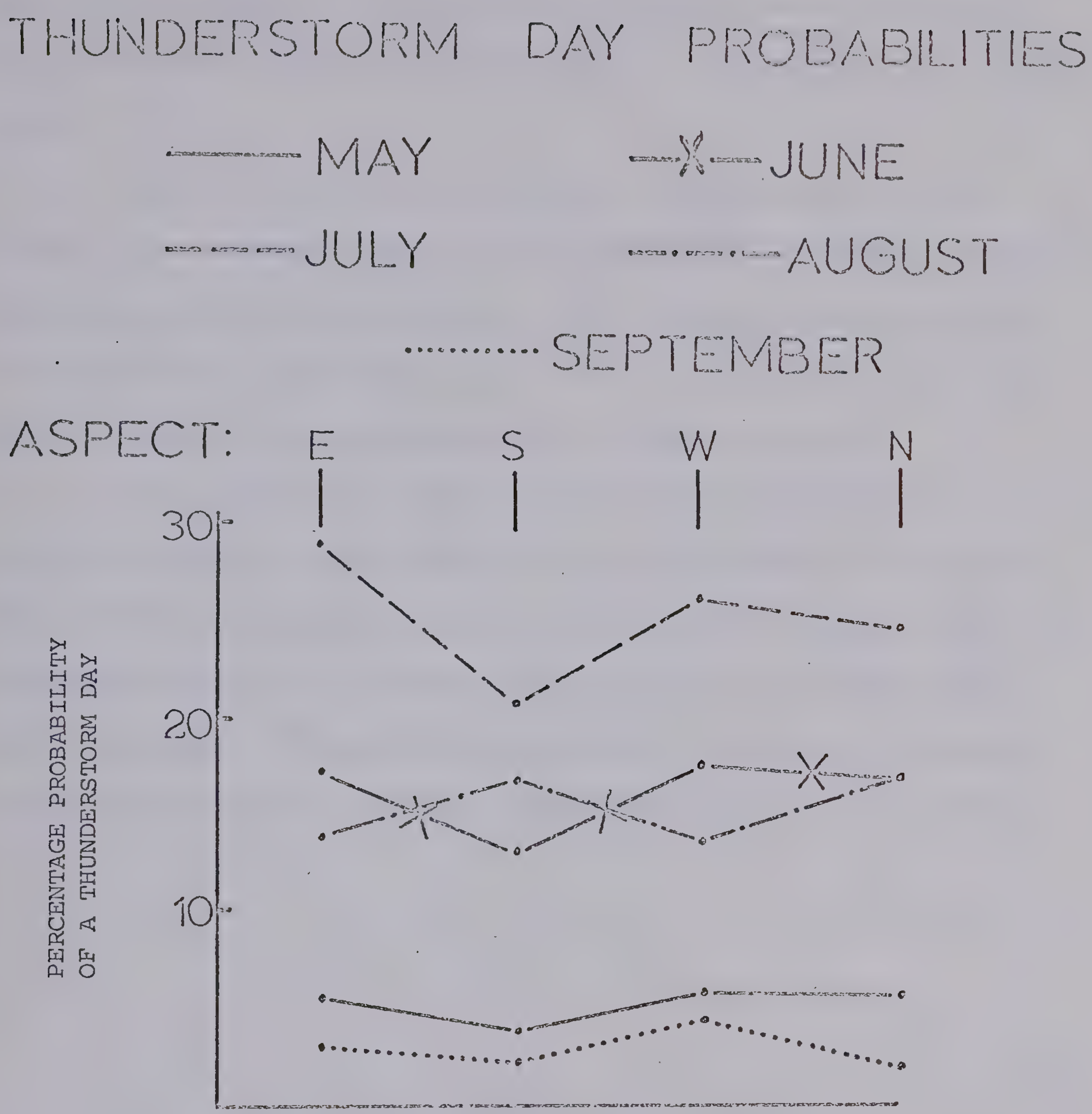

Figure 4.16 MONTHLY PROBABILITIES OF THUNDERSTORM DAYS RELATED TO THE DIRECTION OF SLOPE OF THE OBSERVING SITE.

probabilities occurring over southern and northern slopes. September thunderstorm activity shows a relative maximum over western slopes. This graph demonstrates that thunderstorm day probabilities, after reaching a July maximum on eastern slopes, have a relative maximum which progresses. This progression suggests that the role played by slopes in both modifying the atmosphere and creating thermals is a function of the sun's zenith

angle and day-length. The physics of this effect has already been elaborated on in conjunction with September thunderstorm day probabilities.

Appendix F lists the occurrence of storms by day for the interval from 1962-68. The frequency distribution of active thunderstorm days (arbitrarily defined as a day on which the mean number of storms per year exceeds 38) ranges from June 6 to August 4 with the maximum number of storm reports being received on July 17.

The temporal variations of thunderstorm behaviour on both a diurnal and annual scale provide us with some insight into the processes whereby topography controls thunderstorm development. This control appears to be a function of day-length, solar zenith angle and slope-aspect. Orographic systems exert a control which depends on the distribution of wind with height throughout the troposphere.

CHAPTER V

THE SPATIAL DISTRIBUTION OF THUNDERSTORMS

When ye see a cloud rise out of the west, straightway ye say, There cometh a shower and so it is. (Luke 12:54)

5.1 INTRODUCTION

The preference of showery, convective clouds to form in certain areas has been recognized since antiquity. Unfortunately operational meteorologists have rarely, if ever, been provided with a quantitative procedure for incorporating their knowledge of such preferences into a forecasting technique. Although this study does not provide such a procedure, it does locate these preferred areas and to some extent the physical processes responsible for their existence. Introducing such new information into the analysis could provide a technique capable of increasing the precision of thunderstorm forecasts.

In order to locate these areas, modal and mean initial bearings were analyzed. Using the CCC technique, the effects of storm location on other storm characteristics were examined. The spatial and seasonal distribution of mean initial bearings and the per cent relative frequencies of thunderstorm formation in each octant about each lookout are discussed. A model based on the information gleaned from the ALR technique is combined with conclusions drawn in Chapter 4 to explain the effects of orography on thunderstorms.

5.2 MODAL INITIAL BEARINGS

In order to locate the areas of preferred storm development

the initial bearings were analyzed. Frequency distributions smoothed by a symmetric, triangular filter (see Chapter 3) were analyzed. The modal angles of attack for each station having at least 3 years of data were calculated and subsequently plotted on an Alberta Forest Service map. Only those modal angles[1] from which at least 7.5 per cent of the stations' storms approached were considered significant enough to include. Each of the arrows shown in Figure 5.1 indicate the direction from which storms most frequently approach the station at the base of the arrow. Two arrows pointing from different stations to the same location imply the observers are reporting the same clouds. Based on this observation, areas where the arrows converge must represent areas of preferred storm development.

Inspection of Figure 5.1 shows the existence of definite storm tracks. One track appears in the northern Edson Forest along the eastern slopes of the Rocky Mountains. Another track appears to the south of the Thickwood Lookout along the southern slopes of the Thickwood Hills. Similarly thunderstorms form and travel along the south-eastern slopes of the Birch Mountains and the eastern slopes of the Clear Hills. In the southern forests thunderstorms appear to be associated with localized topographic features, while the two most southerly forests have very few stations which meet the criterion for having a preferred direction. The hatched areas in the Clearwater-Rocky Forest are associated with a ridge of foothills which stretch south from Chungo (north-northwest of Baldy (BY)).

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[1] the modal angles used in this analysis are actually initial bearings in ten degree ranges.

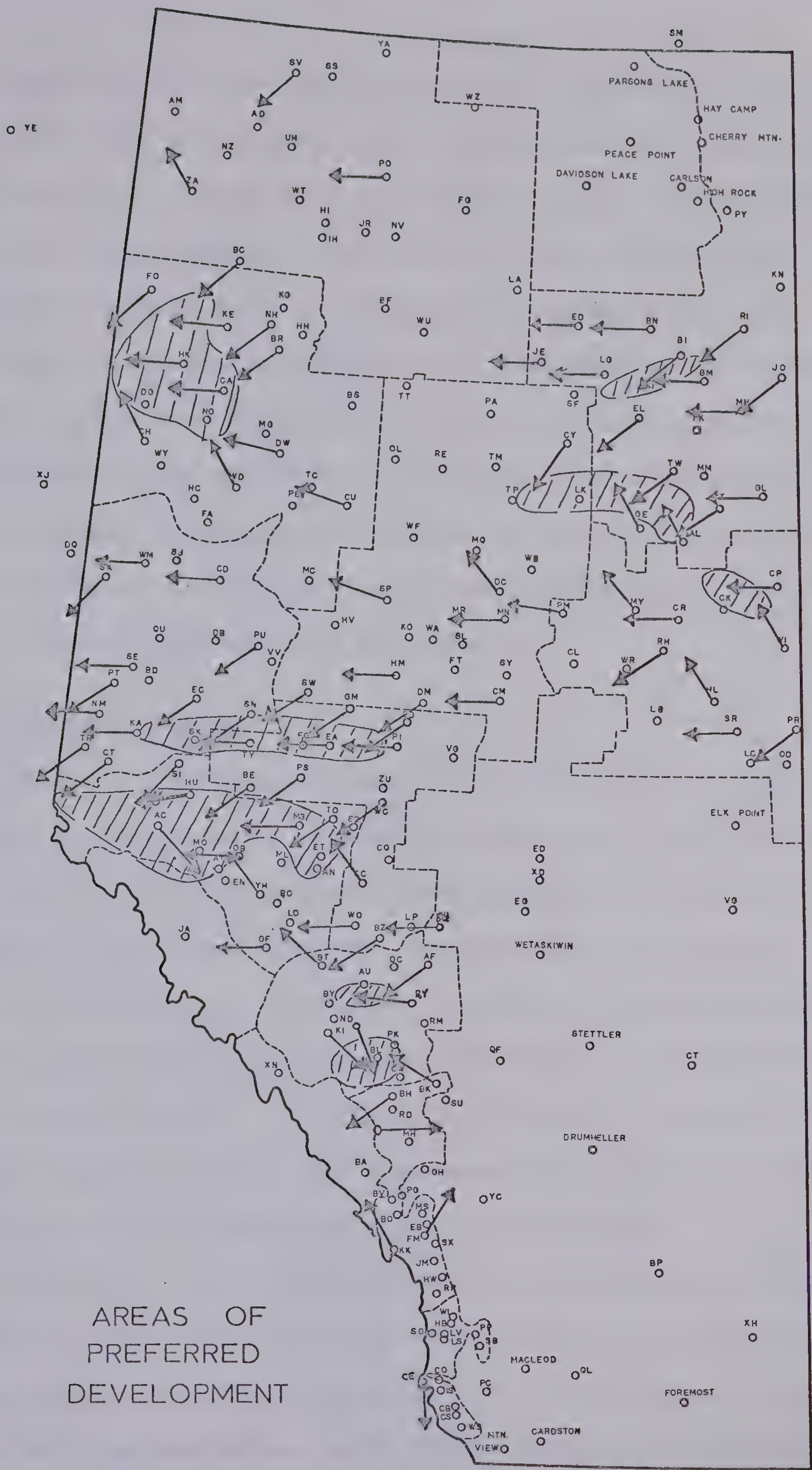

Figure 5.1 THE SPATIAL DISTRIBUTION OF THE MODAL INITIAL BEARINGS. The hatched areas represent regions of preferred thunderstorm development. (see text)

Except for small latitudinal variations synoptic processes produce a uniform distribution of storms. The existence of preferred areas of storm development implies that geographical trigger mechanisms must be initiating thunderstorms. Over northern forests the one-to-one correspondence between the preferred areas and southeastern slopes suggests that some mechanism operating on these slopes may be responsible. The northern Slave Lake Forest, which is devoid of significant topographical features, does not appear to have a preferred area of storm development. The short-term records available for several of the Footner Lake Forest lookouts partially accounts for the lack of defined areas of preferred development in that forest.

5.3 MEAN INITIAL BEARINGS

The mean angles of attack were calculated and then plotted on a map to give the configuration presented in Figure 5.2. The isogones[2] on this map imply that storms in the southern stations generally develop to the south of individual stations. The mean angle of attack for storms in elevated forests was found to be 218 degrees contrasting the mean angle of 226 degrees which characterized thunderstorms occurring over the lowland forests. This anomaly is the natural consequence of the trigger mechanism such as wave phenomena which may be responsible for assisting storm development in the elevated forests.

Areas where storms frequently develop to the east or southeast of individual stations result in mean angles of 180° or less and are denoted by horizontal hatching on Figure 5.2. In areas where strong gradients exist between minimum angles to the west and maximum angles

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[2] an isogone is defined as a line joining points having equal initial bearings.

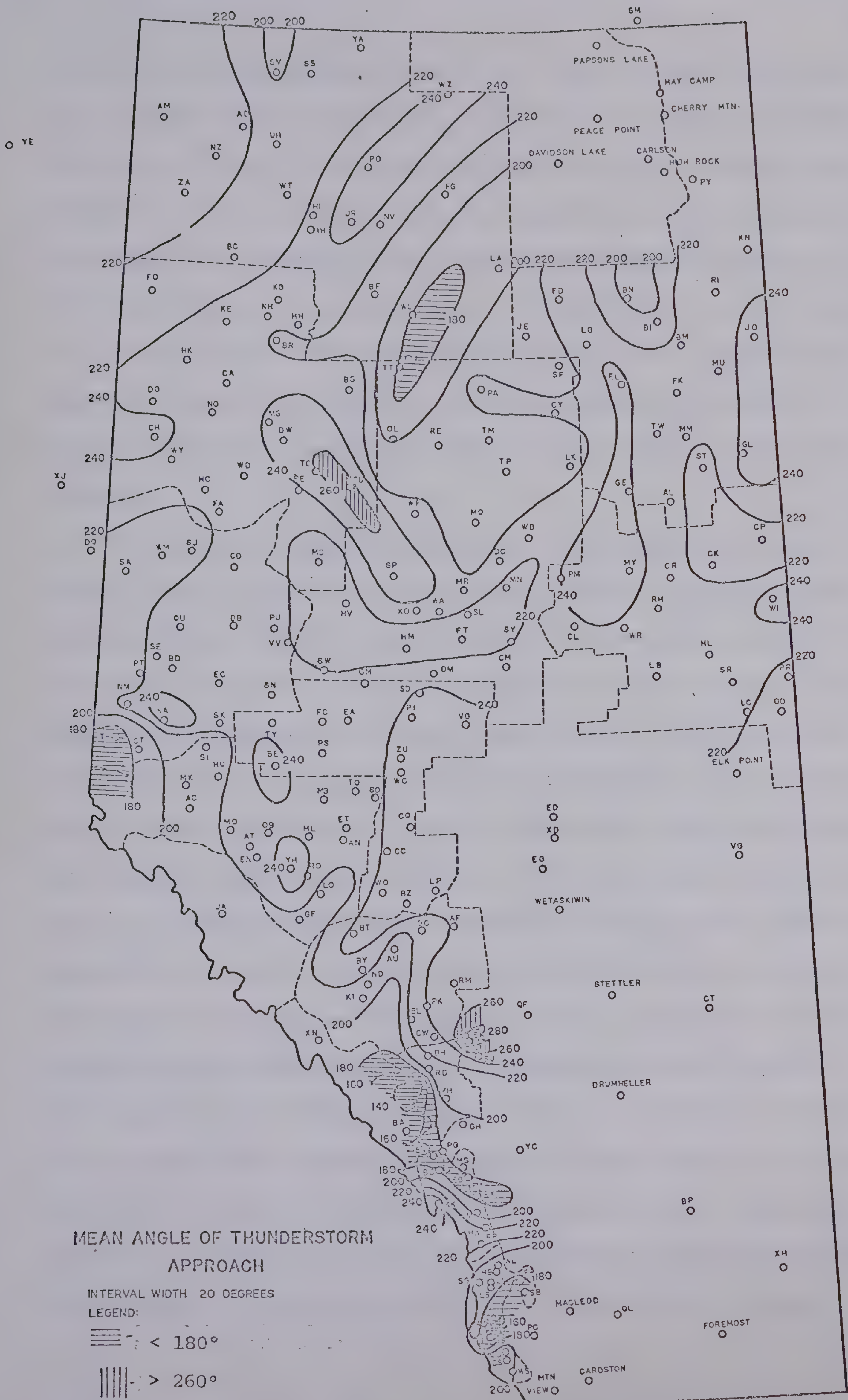


Figure 5.2 THE SPATIAL DISTRIBUTION OF MEAN INITIAL BEARINGS.

to the east, storm development is likely. Lines of storm development exist between Torrens (TR) and Kakwa (KA), in the southwestern Grande Prairie Forest, and in the northern Bow River Forest. This last line appears to be an extension of the area of preferred storm development which Figure 5.1 displayed in the southern Clearwater-Rocky Forest. It is of note that several centers of large averages form 50 miles to the east of major hills. This displacement suggests that the storms have formed over the hills to the west and then have moved into view of observers located in the areas of large average angles of attack from the west.

The -0.37 correlation coefficient which related mean angles of attack to the elevation of lookouts in the elevated forests indicates that thunderstorms tend to form to the east of the higher lookouts. This correlation is in agreement with inferences made from the isogone patterns which suggested that storms moved eastward after forming over the higher terrain. Another interesting relationship arising from the CCC analysis is summarized by the -0.39 correlation coefficient relating mean approach angles and median dates. This coefficient, significant at the 98 per cent confidence limit, implies that early season thunderstorms form to the west of individual stations while the late season storms form to the east. Combined with the first correlation, it is obvious that the trigger mechanisms initiating late season thunderstorms operate at the higher stations. The 0.37 correlation coefficient which relates storm durations and angles of attach suggests that storms approaching from the west persist for a longer time than storms which develop to the east. The nature of the observations explains this apparent relation. If a storm approaches from the west it will normally

proceed through the observer's field of view. If the storm is not in its dissipative stages the observer will report the storm as it moves from his western horizon to his eastern horizon, a process which may take an hour. On the other hand an eastward-moving storm forming to the east of a particular station will spend a short period of time within the observer's view.

The lowland forests demonstrate a relationship between elevation and mean angle of attack similar to that found for thunderstorms over elevated forests. Although only significant at the 95 per cent level of confidence, the -0.28 correlation coefficient suggests that the storms moving into the view of a lowland lookout tend to approach from the west while those seen from lookouts on higher terrain often develop to the east or southeast. Initial bearings for storms over lowland forests are dependent on longitude. The correlation coefficient of -0.29 implies that thunderstorms on the average form more to the east of individual lookouts in the western part of the province than they do in the east. The absence of any significant correlation between the mean initial bearings and the median dates and storm durations in the lowland forests implies that the seasonal effects of the storm generation mechanisms are insignificant. Since areas where such seasonal dependence is present are characterized by rugged terrain, it can be concluded that the processes responsible for the late season storm development observed in the elevated forests are associated with this rough physiography.

The seasonal distribution of the mean daily initial bearings for all forests is shown in Figure 5.3. This graph commences on May 16 and terminates on September 7. The component present at high wave numbers on this graph which exhibits the unsmoothed mean initial bearings

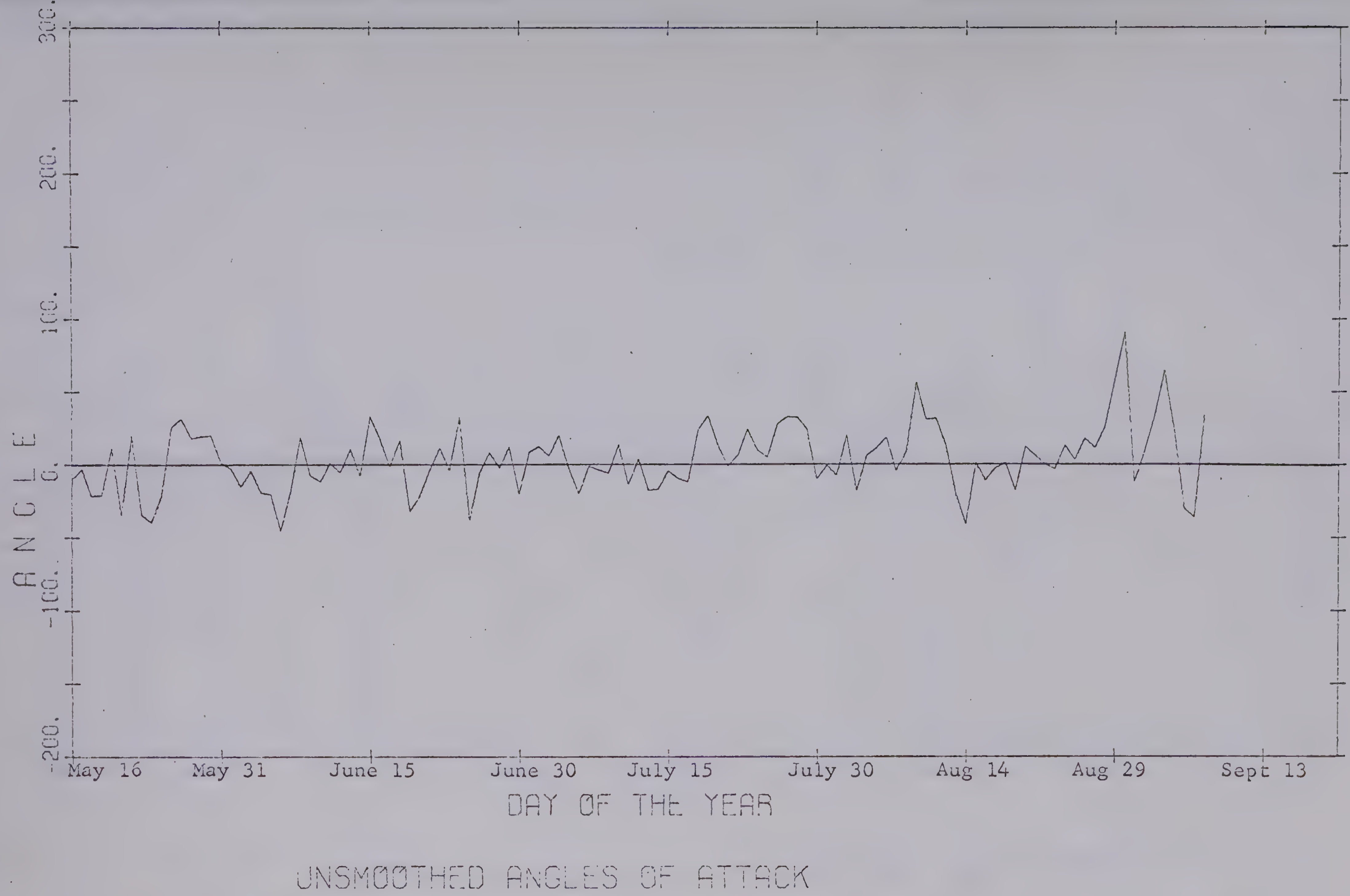


Figure 5.3 VARIATIONS IN THE UNSMOOTHED INITIAL BEARINGS FROM THE SEASONAL MEAN FOR ALL YEARS. The seasonal mean shown by the horizontal line is 227.1 degrees. The plots commence on May 16 and conclude on September 7.

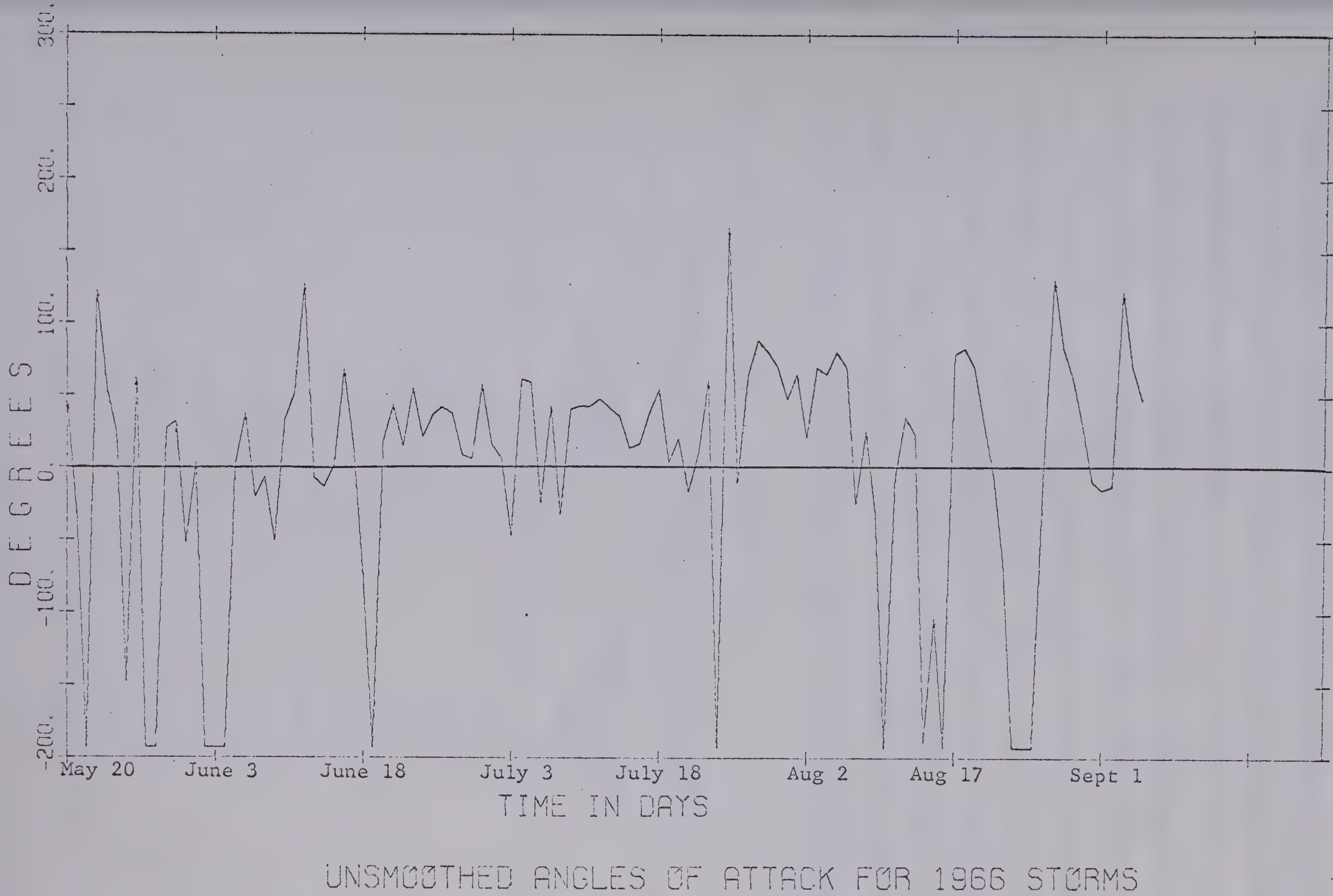


Figure 5.4 VARIATIONS IN THE UNSMOOTHED INITIAL BEARINGS FROM THE SEASONAL MEAN FOR 1966. The seasonal mean is 223.7 degrees. The graph continues from May 20 to September 6.

indicates the mean initial bearings undergo daily variations. The non-existence of a seasonal trend is evident from both the graph and the autocorrelation coefficients given in Table 5.1. The unsmoothed initial bearings displayed in Appendix G do not reflect a marked seasonal variation although the mean approach angles do increase during August. Figure 5.4 contains the daily mean approach angles for 1966. The daily fluctuations appear significant early in the series but become modified during July. The smoothing observed during July is likely the result of the larger number of thunderstorms which occur at this time of the summer. Towards the end of the season storms appear to be approaching individual stations from more westerly angles. It is also noticeable

TABLE 5.1

AUTOCORRELATION COEFFICIENTS FOR INITIAL BEARINGS

LAG	UNSMOOTHED MEAN BEARINGS (r)	SMOOTHED BEARINGS FROM 1966 (r)
0	1.00	1.00
1	0.29	0.54
2	0.19	0.22
3	0.06	- 0.01
4	- 0.03	- 0.10
5	0.06	0.00
6	- 0.04	0.02
7	- 0.04	0.06
8	- 0.02	0.10
9	- 0.07	0.21

that trends appear to persist for 3 day intervals subsequent to August 19. This persistence and increase in mean initial bearings suggests that late season storms are being generated in similar areas by similar processes. Further evidence is required before this supposition can be given a great deal of credance.

5.4 RELATIVE FREQUENCIES OF INITIAL BEARINGS

Although the mean is a useful statistic it often conceals more information than it conveys. In order to uncover some of this information, the horizon about each observing point was divided into octants. The first octant included the sector extending from 1° to 45°. All storms first viewed in this octant are referred to as storms approaching from the north-northeast. The percentage relative frequencies were found by multiplying the number of storms approaching from a specific octant by 100 and then dividing by the total number of thunderstorms viewed from the observing point. As a comprehensive review of the spatial distributions of these relative frequencies and a method of chart interpretation are included in The Preliminary Results of Project Metlite (Lawford, 1970b) only 2 charts will be included here.

Figure 5.5 exhibits the relative frequencies of storm occurrence in the west-southwest. The primary maximum which stretches from the western border to the southeastern extremity of the Whitecourt Forest, suggests that thunderstorms form along the ridges and river valleys to the southwest. The secondary maximum over Deer Mountain (DM) implies that storm development occurs on the southern and southwestern slopes of the Swan Hills. The relative maximum present in the northwestern Athabasca Forest suggests that storms initially form over the Birch Mountains and

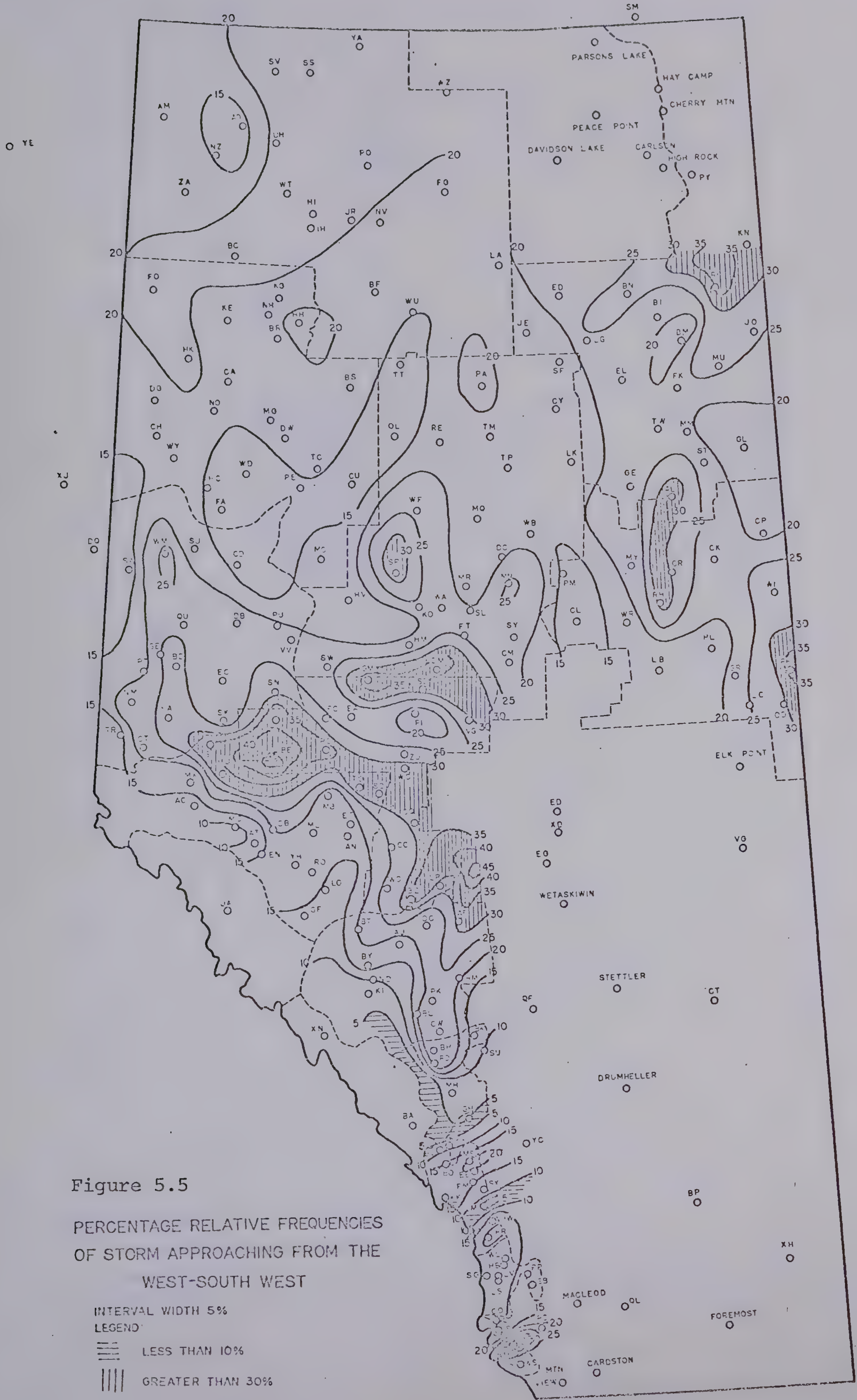


Figure 5.5

PERCENTAGE RELATIVE FREQUENCIES OF STORM APPROACHING FROM THE WEST-SOUTH WEST

INTERVAL WIDTH 5%

LEGEND

LESS THAN 10%

GREATER THAN 30%

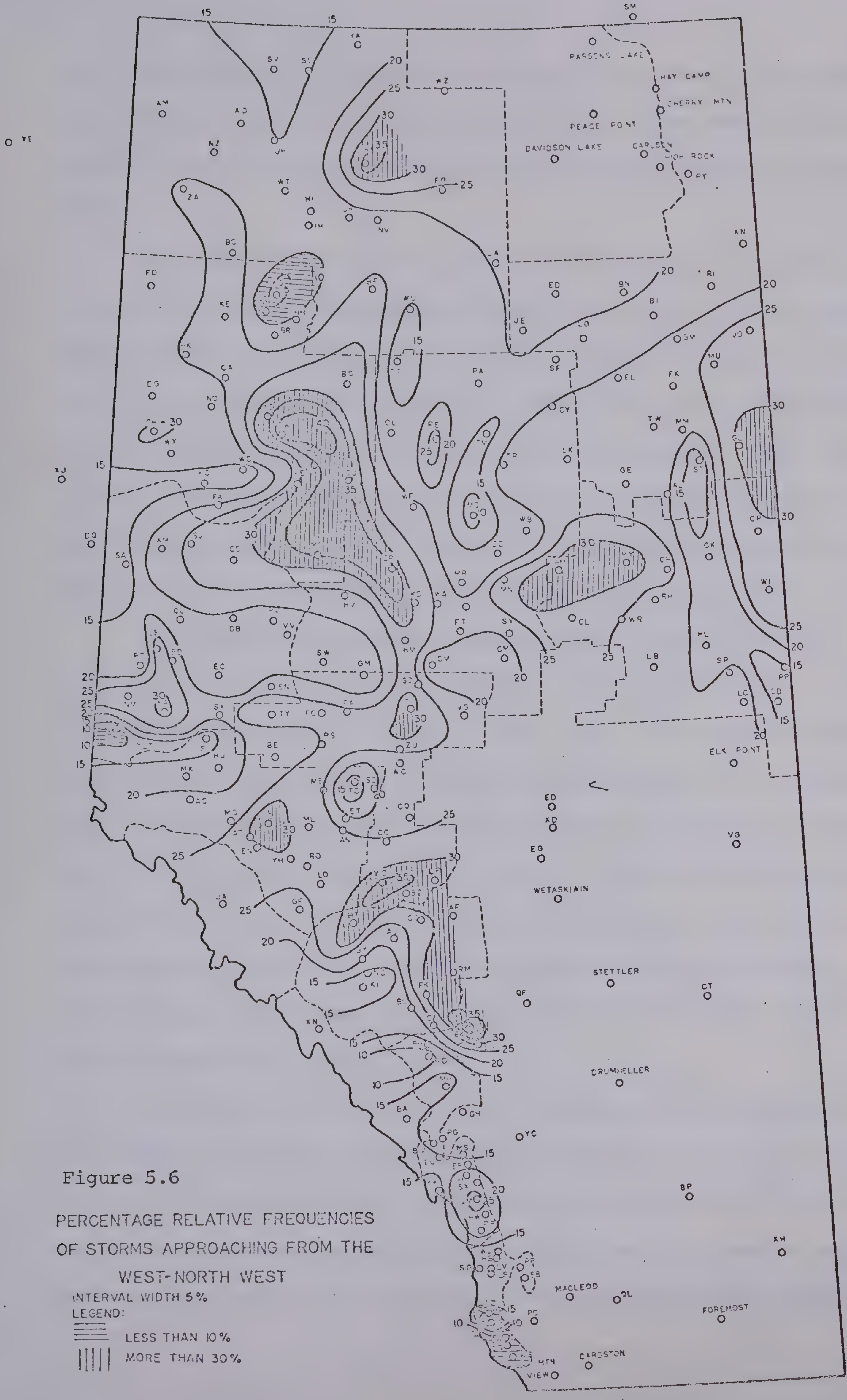


Figure 5.6

PERCENTAGE RELATIVE FREQUENCIES OF STORMS APPROACHING FROM THE WEST-NORTH WEST

INTERVAL WIDTH 5%

LEGEND:

LESS THAN 10%

MORE THAN 30%

then travel eastward. The highly localized extrema which characterize the southern forests support the validity of an earlier conclusion regarding the very localized trigger mechanisms initiating foothill thunderstorms.

The method of graphical localization assists in determining the location of preferred thunderstorm development. If we consider a maximum in the isopleths of Figure 5.5, such as the one centered at Berland (BE) to the northeast of the minimum at Moberly (MO), we conclude that the intermediate zone is an area of preferred development. The extent to which the chart of relative frequencies for the east-northeastern octant gives a mirror image of this pattern provides a measure of the validity of the results of this method for a specific location.

On Figure 5.6 the isopleth patterns associated with storms sighted in the west-northwest are organized into several maxima. Similar to the relative maximum in the Peace River Forest, the relative maxima in the southern Whitecourt and eastern Clearwater-Rocky Forests suggest that thunderstorms are developing over the higher terrain to the west. The strong gradient which separates Burnstick (BK) from her western neighbours exemplifies the affects of storm development over higher terrain on the patterns of Figure 5.6. Again the southern forests are spotted with isolated maxima and minima which result from the small-scale nature of trigger mechanisms in the mountains.

In order to demonstrate the relationships between topography and the relative frequencies of thunderstorms sighted in each octant, Figures 5.7 and 5.8 were constructed. The correlation coefficients (r_{E-A}) between the per cent relative frequencies of thunderstorms first seen in each octant and the elevation for stations in both the elevated and lowland

forests are shown in Figure 5.7. The abscissa for both Figures 5.7 and 5.8 are labelled with symbols which denote the octant being referred to. For example, NE-E refers to the set of all initial bearings between 46 and 90 inclusive.

Figure 5.7 shows that the correlation coefficient (r_{E-A}) varies systematically between octants. The negative correlation coefficient for the southerly octants demonstrate the tendency for thunderstorms at lower stations within the elevated forests to be sighted from the west-southwest. From the positive correlation present in the easterly octants we conclude that the thunderstorms occurring over higher terrain are likely to manifest themselves to the east and northeast of the individual lookouts. These correlations support inferences made from earlier charts regarding the tendency of thunderstorms to form to the east and east-southeast of the high mountain lookouts in the southern forests.

The correlation coefficient (r_{E-A}) does not vary consistently from octant to octant in the lowland forests. It appears that the variations arise from random fluctuations which are superimposed on the trend towards negative correlation coefficients for the more westerly octants. Although a positive correlation exists between elevations and relative frequencies for all eastern octants, only in the east-southeast is a significant correlation coefficient realized. The + 0.3 coefficient indicates that a larger proportion of the storms forming over the higher terrain will first be visible in the east-southeast. The results of this graph indicate that hills are influential in initiating thunderstorms in the lowland forests.

The role of station location in determining the angles at which thunderstorms will be first sighted was inferred from graphs of longitude

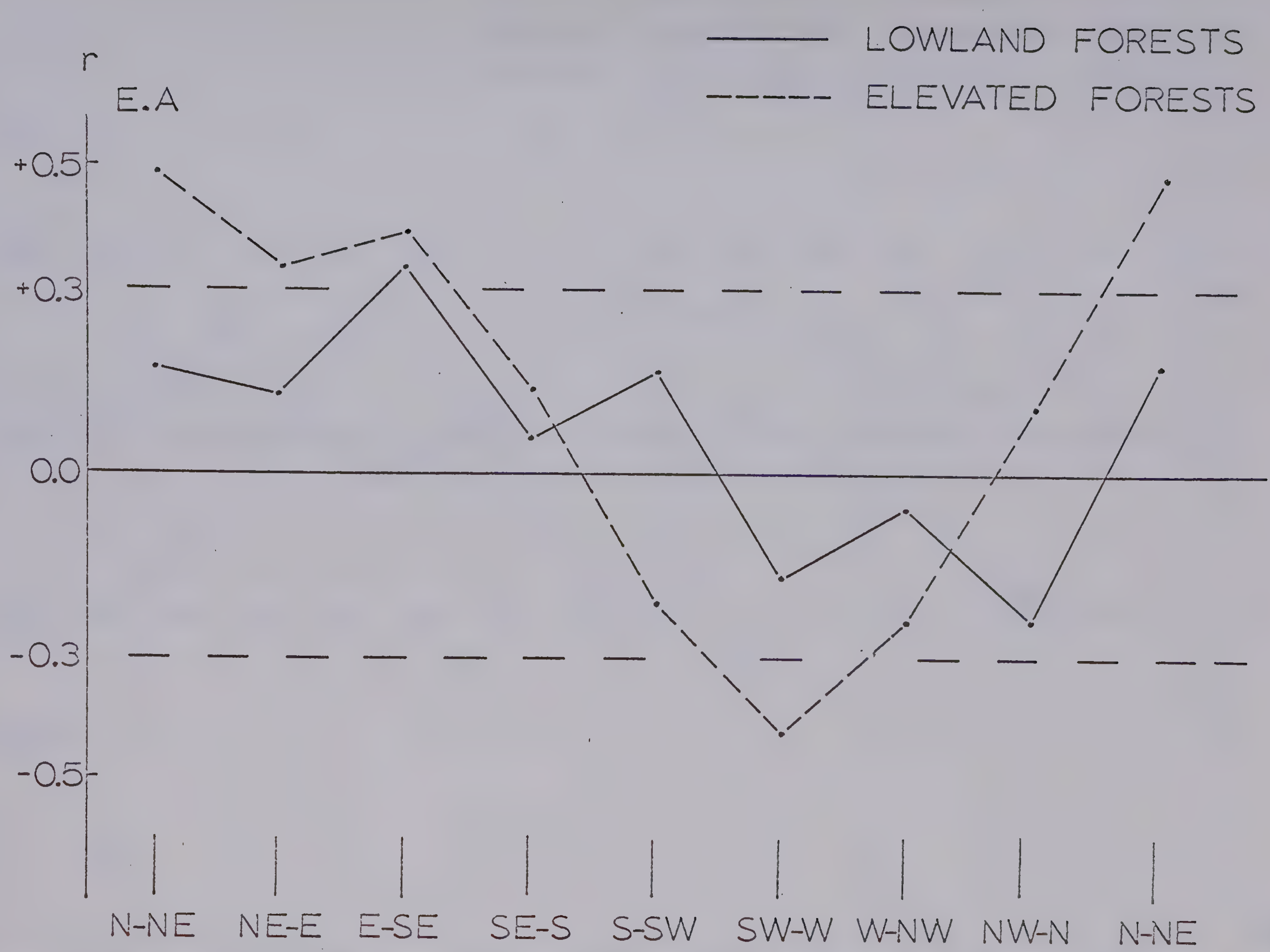


Figure 5.7 THE RELATIONSHIPS BETWEEN ELEVATION AND THE RELATIVE FREQUENCIES OF STORMS SIGHTED IN A PARTICULAR OCTANT. The correlation coefficients are given along the ordinate.

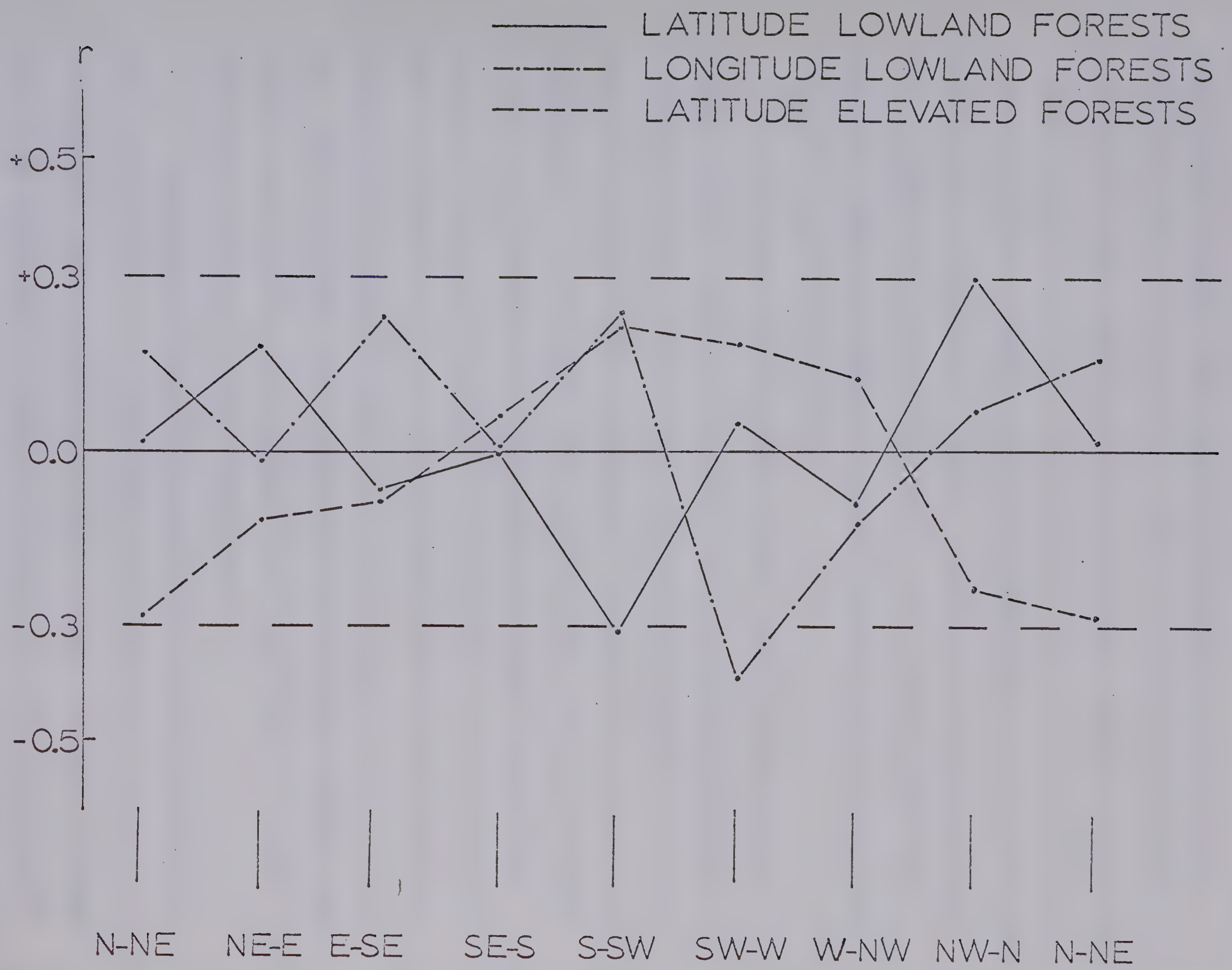


Figure 5.8 THE RELATIONSHIPS BETWEEN STATION LOCATION AND THE RELATIVE FREQUENCY OF STORMS SIGHTED IN A PARTICULAR OCTANT. Correlation coefficients are given along the ordinate.

and latitude. Although these relations are partially revealed by the individual correlation coefficients listed in Appendix H, Figure 5.8 indicates the trends that exist in the relationships between station location and approach angles. Over the elevated forests the only significant correlation between elevation and relative frequencies of initial bearings occurs in the north-northeast. However the variation from octant to octant is smooth with positive correlations in the southern octants indicating that storms over the more northerly elevated forests develop over the higher terrain to the southwest.

Correlations over the lowland forests result in disorganized graphs. The correlation between latitude and the relative frequencies of angles of attack indicate that latitude has some effect on the mechanism initiating thunderstorm development. The solid line on Figure 5.8 representing this correlation varies from a negative value in the south-southwest to a positive value in the north-northwest. The fact storm development occurs to the southwest of low latitude western lowland lookouts is not surprising since this is an area of higher terrain and has already partially been delineated as an area of preferred storm development. This correlation also suggests that storms in the southern lowland forests tend to travel to the northeast while those present in higher latitudes prefer to move south-southeastward.

The correlations between longitude and the various octants over the elevated forests do not show anything of significance, and hence are not included. The correlations for lowland forests do not vary systemmatically but they do show a significant negative correlation coefficient in the west-southwestern octant. This coefficient which can be accepted at the 95 per cent level of confidence suggests that thunderstorms in the

eastern part of the province prefer to develop to the west-southwest. The large variation in the coefficient between the S-SW and the W-SW indicates that storms in the western part of the province are initiated by more southerly trigger mechanisms.

A plot of the correlation coefficients relating onset times and the relative frequencies of angles of attack shows a minor trend in the lowland forests and no organized trend in the elevated forests. The graph included in Appendix I indicates that a significant negative correlation relates onset times to frequency of thunderstorms in the east-northeast while a positive correlation exists between onset times and storms in the east-southeast. The negative correlation implies that storms forming to the east-northeast will occur early in the day while stations with a high frequency of storms attacking from the east-southeast view them later in the afternoon. This suggests that the areas of preferred early afternoon storm formation are located to the east-northeast of the higher terrain from which these storms are most frequently viewed.

5.5 THE EFFECTS OF OROGRAPHY ON STORM DEVELOPMENT

The ALR technique was applied to approach angles and resulted in Figure 5.9. From this graph it appears that the thunderstorms which develop to the south and east of stations in zone 2 advect eastward and northeastward into zones 3, 4 and 5. The fact that storm development occurs between zones 2 and 3 implies that some mechanism resulting from the presence of the mountains must be affecting the growth of these storms.

The growth of thunderstorms 70-80 kilometers downstream from the Continental Divide implies the existence of a mesoscale wave such as Dirks et al (1967) postulate. Their wave which exists under conditions of

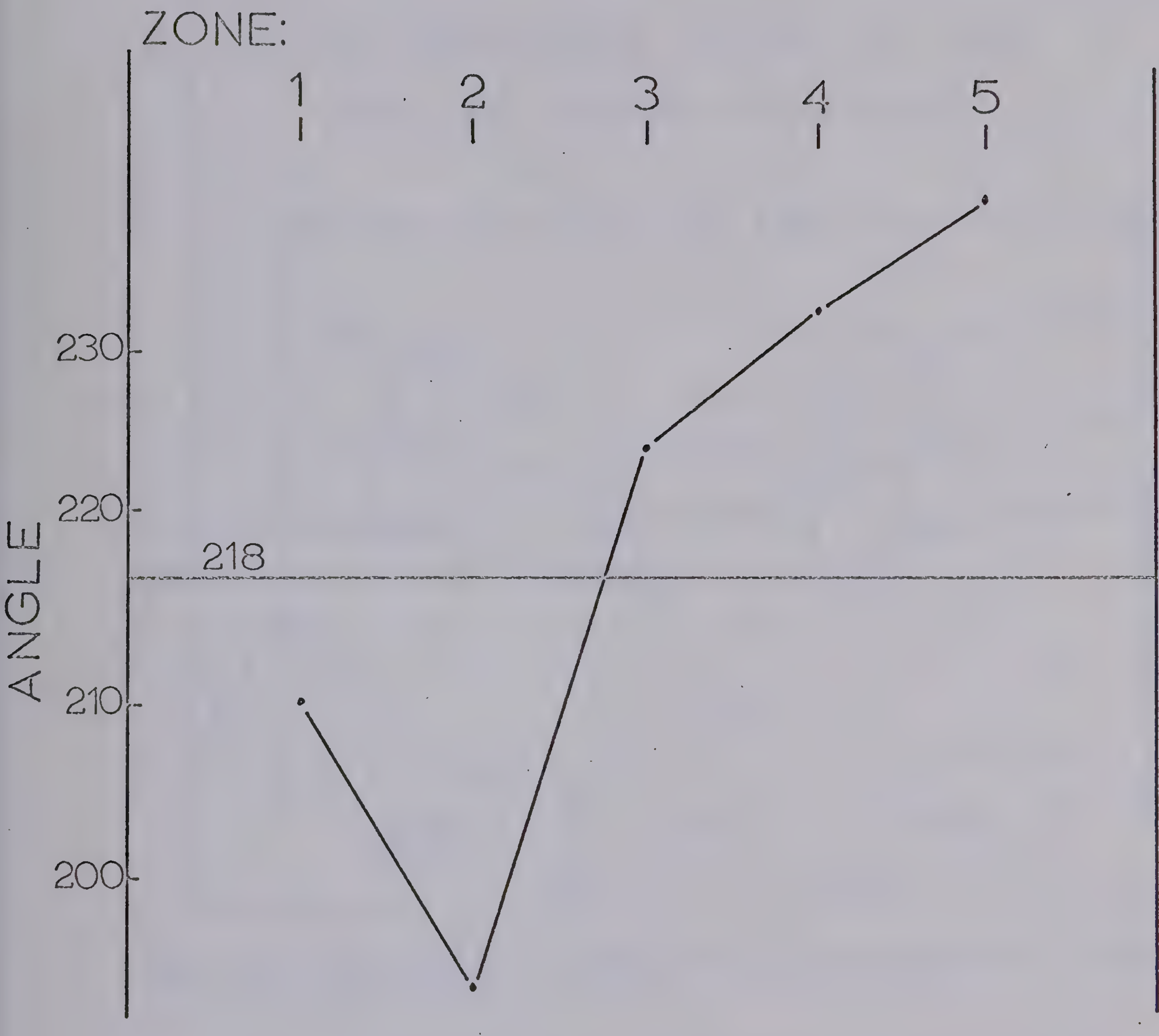


Figure 5.9 VARIATIONS IN THE MEAN INITIAL BEARING EAST OF THE CONTINENTAL DIVIDE.

low stability and weak wind shear was thought to affect the development of western United States thunderstorms in a similar fashion, suppressing their growth immediately to the lee of the Divide and accentuating their growth further downstream.

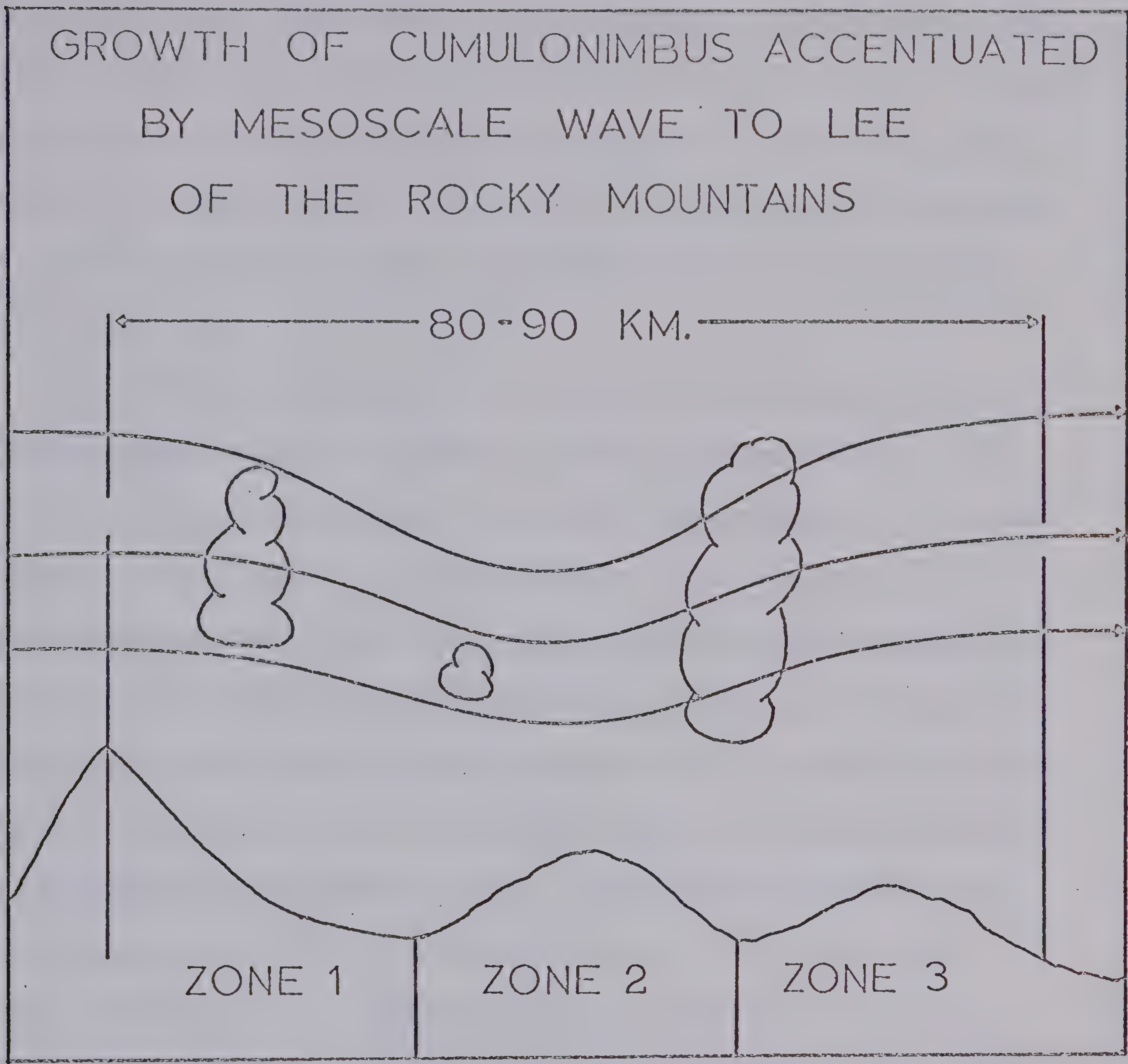


Figure 5.10 THE EFFECTS OF A MESOSCALE WAVE ON THE DEVELOPMENT OF CUMULONIMBUS CLOUDS.

Such a wave phenomenon in Alberta would not initiate thunderstorms, but only accentuate the growth of existing thermals. The wave would act to destabilize the atmosphere between forty and eighty kilometers east of the Continental Divide. Although the actual processes require further examination, the stretching of air columns present between the trough and the ridge will partially account for the observed effects.

This wave by nature of its derivation is an average wave. Although Paul's results (Paul, 1967) supply further evidence of its existence based on the wavelike structure of hailfall patterns the dimensions, the structure and even the existence of this wave for an individual day remains to be demonstrated. Based on Figure 5.9 and the results of Chapter 4 the mesoscale wave must have a wavelength of 80-90 kilometers. The wave is shown in Figure 5.10.

An alternate explanation for the wave-like structure present in thunderstorm characteristics to the lee of the mountains (which in the case of thunderstorms extend only one wavelength downstream) can be found in Thyer's (1970) results. He suggested that a thermal chimney was responsible for the low-level flow towards the mountains and the upper level outflow from the mountains indicated by Calgary's afternoon winds. Since the presence of the vertical motions necessary to create such local circumstances would be found over the eastern slopes of the Rocky Mountain Range, thunderstorm development in zone 2 would be stimulated by this effect. The subsidence which is generally present in the air after crossing the Divide would suppress thunderstorm formation in zone 1, leading to the apparent wavelike structure in thunderstorm characteristics. Whether orogenic storms develop as a result of mesoscale wave phenomena or some combined effects of flow over a barrier and differential heating, orography must affect both the temporal and spatial distributions of thunderstorms as well as the intensity and attributes of their associated severe weather phenomena.

CHAPTER VI

SEVERE WEATHER PHENOMENA

And the Lord sent thunder and hail, and the fire ran along the ground : and the Lord rained hail upon the land of Egypt. So there was hail, and fire mingled with the hail .... (Ex. 9:23, 24)

6.1 INTRODUCTION

Severe weather often accompanies well developed cumulonimbus clouds. Under Moses' direction, the Lord's cloud of judgement unleashed thunder, hail and fire-producing lightning flashes. Although rareties in Egypt, hail and lightning are not strangers in Alberta. As hail has been studied by other investigators (Thompson (1970), Paul (1967) etc.) this chapter restricts itself to the devastating severe weather phenomena which result from the distribution of charge within a thundercloud.

In this chapter the annual occurrence of cloud-to-ground charge transfers are discussed. The effects of time, topography, and orography on discharge rates and the average number of strikes per storm are considered. By analyzing the character of lightning strikes inferences about the thundercloud's electrification and development are made. The chapter concludes with a brief discussion of the relationship between hailstorms and thunderstorms in Alberta.

6.2 ANNUAL FREQUENCY OF CLOUD-TO-GROUND FLASHES

Based on our discussion of preferred areas of thunderstorm development and the assumption that a linear relationship exists between

the number of cloud-to-ground flashes observed at a particular location and the frequency of thunderstorms, organized maxima would be expected in the spatial distribution of cloud-to-ground strikes. Figure 6.1 displays the distribution of the annual number of lightning strikes. The maxima on this figure appear to be associated with topographical features present in the lowland forests. The three major relative maxima occur over the Thickwood Hills in the Athabasca Forest, the Swan Hills in the Southern Slave Lake Forest, and the Buffalo Head Hills in the Footner Lake Forest. The location of these maxima and their surrounding gradients suggest that more cloud-to-ground flashes occur over the western slopes. In the case of the maximum over the Thickwood Hills a positive correlation exists between thunderstorm occurrence and the number of cloud-to-ground flashes. The other maxima, which occur in areas where the annual frequency of thunderstorms is only average, imply that the electrical activity of the cloud exhibited by cloud-to-ground flashes depends on the nature of the topography or the stage of the thunderstorms' development or both.

In the southern forest several relative maxima can be located. These maxima, much less intense than those present in the lowland forests, are caused by the lower frequencies of thunderstorm occurrence and, probably, by the variations in the character of elevated forest thunderstorms.

If we assume that an observer views all flashes within a 15-mile radius of his location, 2 cloud-to-ground discharges must occur annually over each square mile near Bitumont (BM). Although the observer will see flashes from nocturnal thunderstorms at distances up to 40 miles, the flashes not observed because of the biases mentioned in

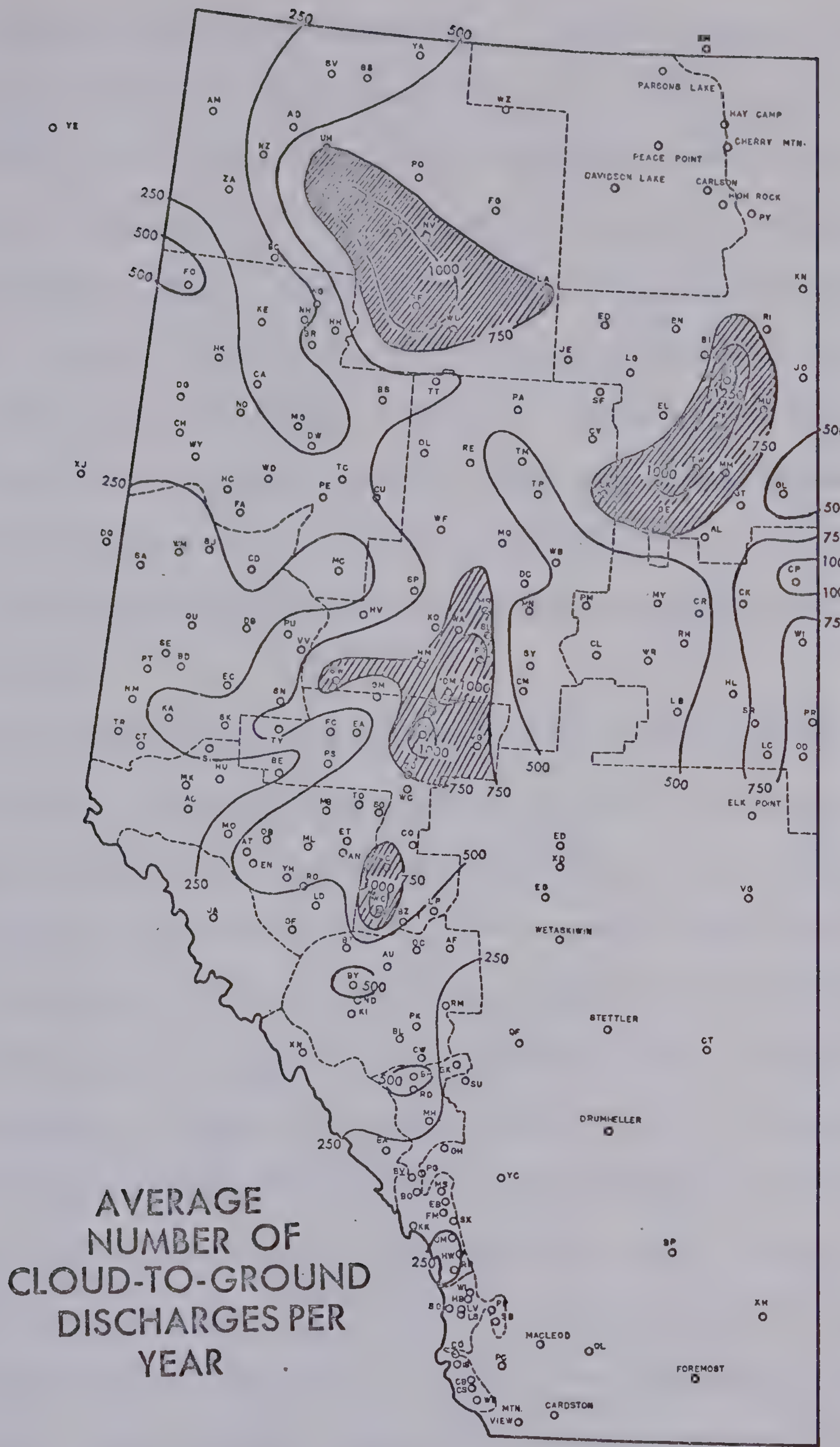


Figure 6.1 THE SPATIAL DISTRIBUTION OF THE ANNUAL NUMBER OF CLOUD-TO-GROUND DISCHARGES OVER ALBERTA FORESTS.

Chapter 3 make a 15-mile radius realistic. From this maximum, the density of the annual frequency of cloud-to-ground flashes decreases to 1 cloud-to-ground flash per 3 square miles in the Crowsnest Forest. This maximum density is less than the 7 cloud-to-ground discharges observed in England (Schonland, 1953). As the difference in latitude between England and Northern Alberta is small, the effects of geographical setting on both the number of and electrical activity of thunderstorms must account for this variation. According to Malan (1963) each flash transfers -20 Coulombs to the earth's surface. Each square mile in the Thickwood Hills receives a net negative charge of -40 Coulombs during the season of convective activity.

If the theories of Vonnegut are correct, positive point discharges amounting to 40 Coulombs per annum would be necessary to charge the cumulonimbus clouds aloft. Because more surface point discharges occur in the vicinity of the Thickwood Hills than in other areas where less charge is transferred aloft it could be postulated that minerals of higher conductivity are present in the Thickwood Hills. Because the other two maxima on Figure 6.1 form over higher terrain, the decreasing distance between a constant-based cloud and the terrain as the cloud moves toward higher ground may be responsible for these maxima. Following Vonnegut's speculations, the reduced attenuation of the influx of rising positive ions would result in rapid charge separation within the cumulonimbus. A more realistic explanation of hill effects (discussed in conjunction with Figure 6.7) recognizes the intensification of the potential gradient under the cloud as it moves towards higher terrain.

The annual number of cloud-to-ground flashes are present in Table 6.1 along with the frequency of lightning-caused fires.

TABLE 6.1

ANNUAL TOTAL NUMBER OF CLOUD-TO-GROUND FLASHES OBSERVED

YEAR	TOTAL NO. OF CLOUD-TO-GROUND DISCHARGES	FREQUENCY OF LIGHTNING FIRES
1965	59,387	124
1966	50,704	108
1967	71,400	297
1968	45,408	116

It is interesting to note that in almost all cases the years with more lightning strikes were years in which more lightning-caused fires occurred.

Figure 6.2 displays the variations in the hourly totals of cloud-to-ground flashes. This histogram shows that 78 per cent of the flashes occur between 1600 and 2100 MST. The time interval during which the maximum number of flashes are observed is roughly the interval during which most of the thunderstorms occur. The fact that the electrical activity persists until 2200 MST, approximately 2 hours longer than maximum thunderstorm activity suggests that evening storms produce more cloud-to-ground discharges than do early afternoon thunderstorms.

The seasonal distribution of lightning discharges per day is shown in Figure 6.3. The graph has been smoothed by a triangular filter with a 7-day width. The interval between June 1 and July 18

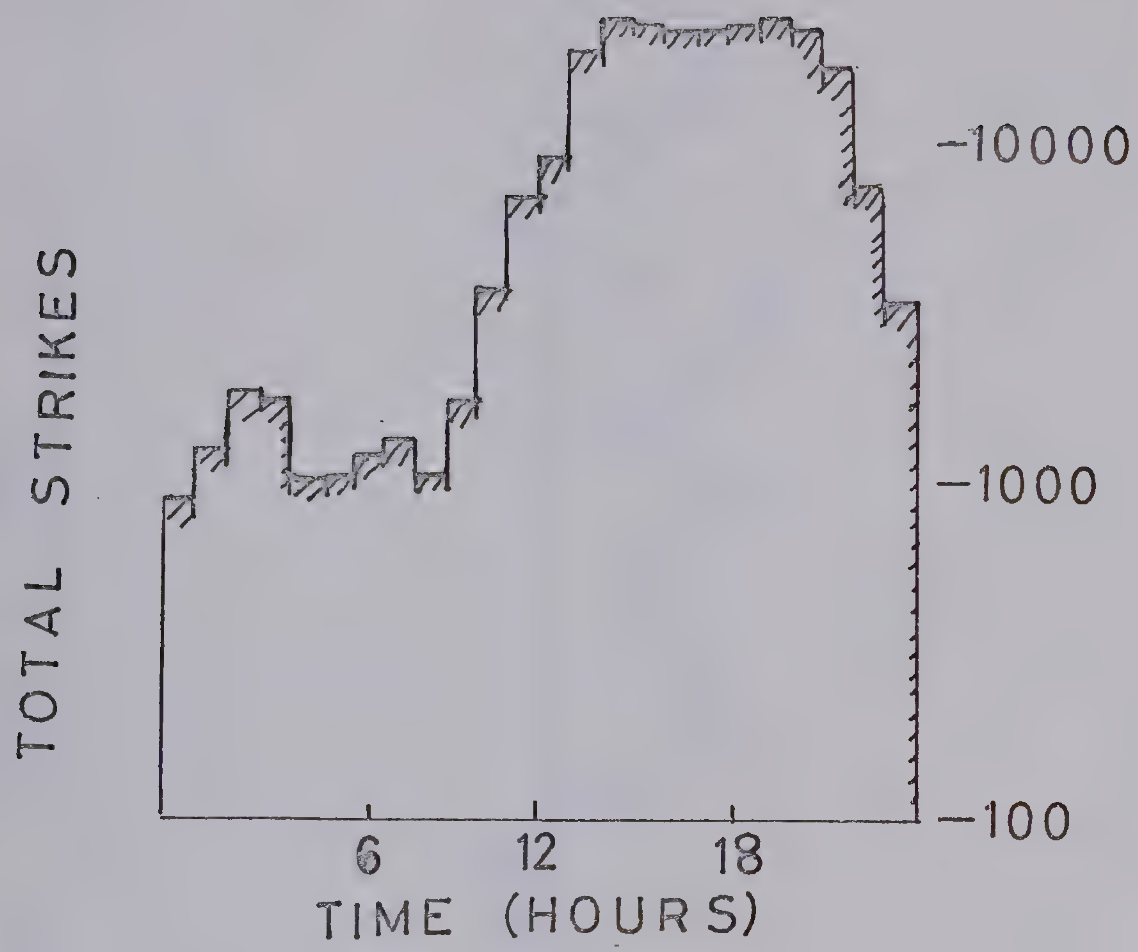
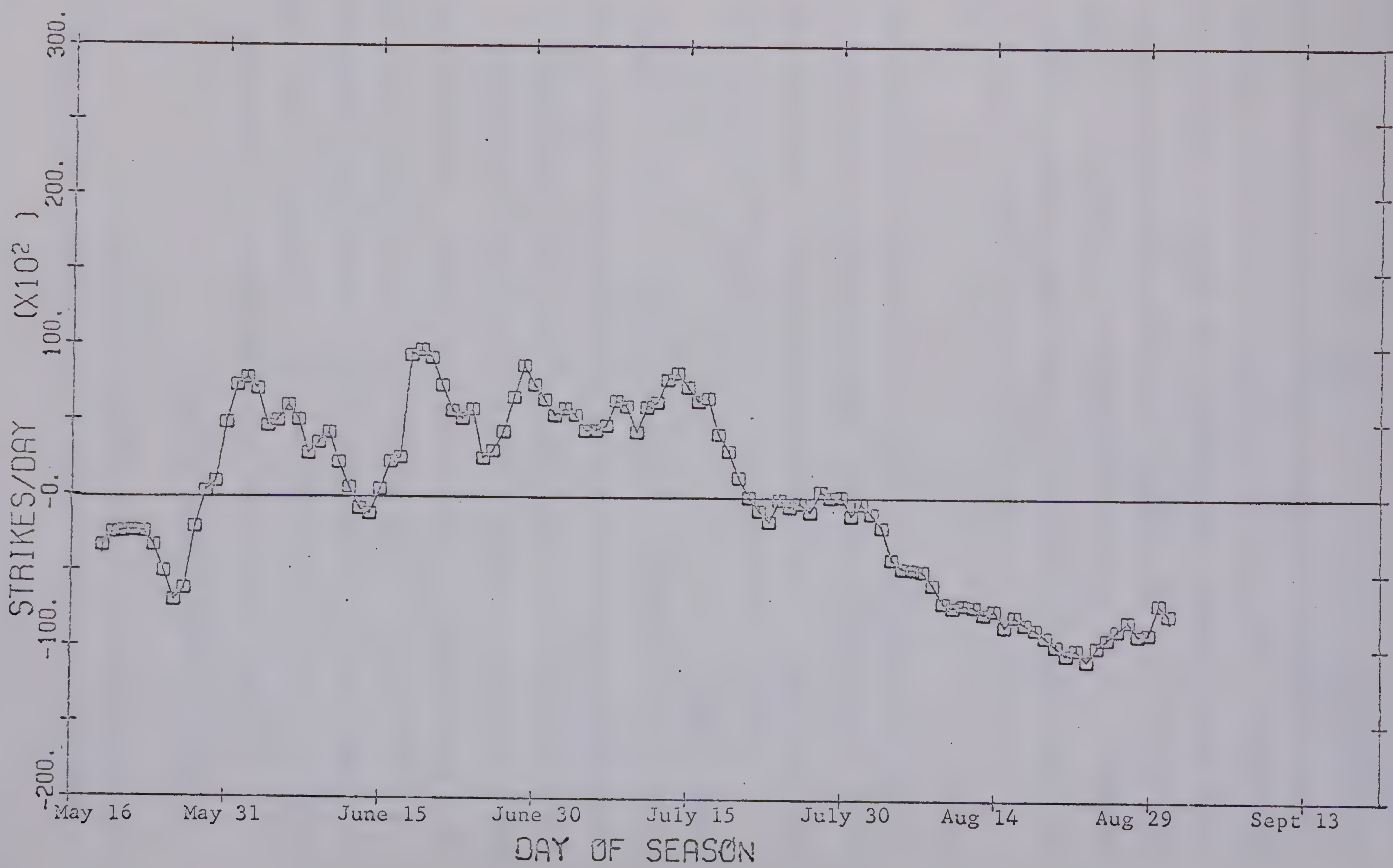


Figure 6.2 DIURNAL VARIATION IN THE TOTAL NUMBER OF CLOUD-TO-GROUND DISCHARGES.

is marked by frequent cloud-to-ground flashes. The shape of the graph coincides quite well with Figure A.2 although it appears that the number of lightning-caused fires decreases one to two weeks earlier. The decrease in strikes per day during August suggests that thunderstorms during this month are either infrequent, or electrically inactive, or both. Appendix F suggests that the lack of late-season storms is responsible for the observed trend. The cyclic variations appearing in



NUMBER OF STRIKES PER DAY

Figure 6.3 VARIATIONS IN THE SEASONAL DISTRIBUTION OF DAILY MEAN NUMBERS OF LIGHTNING STRIKES FROM

the number of strikes per day result from the short-term statistics being considered rather than a climatic variation.

6.3 AVERAGE NUMBER OF STRIKES PER STORM

In order to analyze the spatial distribution of the average number of strikes per storm Figure 6.4 was constructed. In the southern Slave Lake Forest at Flat-Top Tower (FT) or Moberly (MO) a thunderstorm will produce on the average more than 55 flashes. Other relative maxima occur in the Athabasca and the Footner Lake Forests, suggesting that storms which produce a large number of strikes are associated with topographical features in the lowland forests. Only three isolated maxima exist in the southern forests which suggests that these thunderstorms are not sufficiently organized to produce frequent cloud-to-ground flashes.

Over the elevated forests, a 0.39 correlation coefficient relates the strikes per storm and the storms duration. This is an expected relationship because those storms remaining in an observer's view for longer periods of time would be expected to produce more discharges.

Two interesting correlations relate the average number of cloud-to-ground flashes per storm over lowland forests to both longitude and elevation. The -0.66 correlation coefficient relating the mean number of flashes to longitude suggests that storms in the eastern portions of the province produce more lightning than do storms in western Alberta. This tendency is quite evident in Figure 6.4. The -0.41 correlation between elevation and the number of strikes per storm suggests that active electrical storms tend to occur over the lower terrain in the eastern part of the province. Over the lowland forests a significant

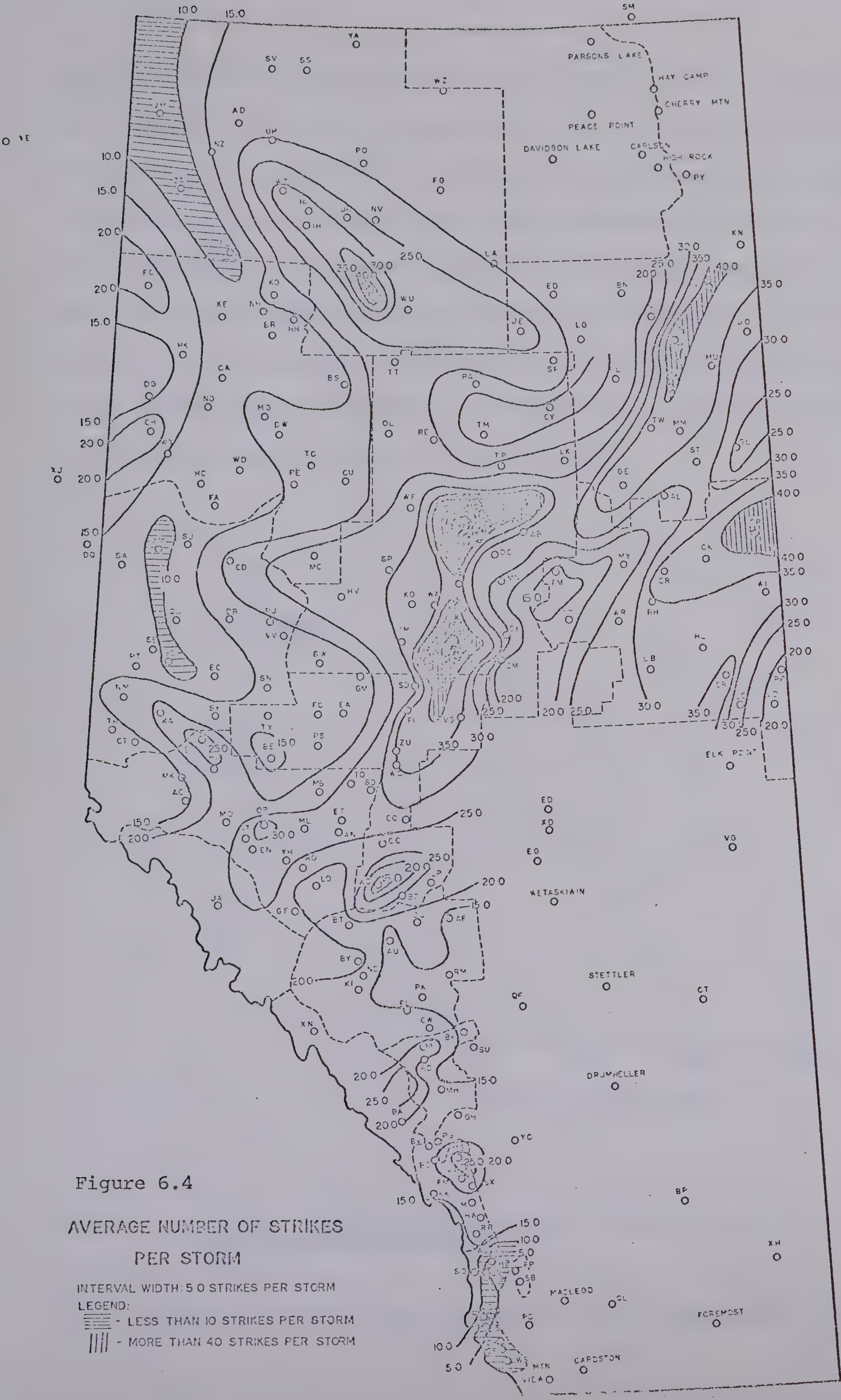


Figure 6.4

AVERAGE NUMBER OF STRIKES PER STORM

INTERVAL WIDTH: 5.0 STRIKES PER STORM

LEGEND:

- LESS THAN 10 STRIKES PER STORM
- MORE THAN 40 STRIKES PER STORM

correlation between storm duration and the average number of strikes per storm does not exist. It appears that the generation of cloud-to-ground flashes is related to the thunderstorm's structure rather than its lifetime or its duration within view of one particular station. This lack of correlation dismisses the idea that the negative relation between longitude and the generation of cloud-to-ground discharges was due to observing bias. Without this result it could have been argued that storms in the eastern lowland forests can be observed for a longer time interval and as a result more discharges would be counted.

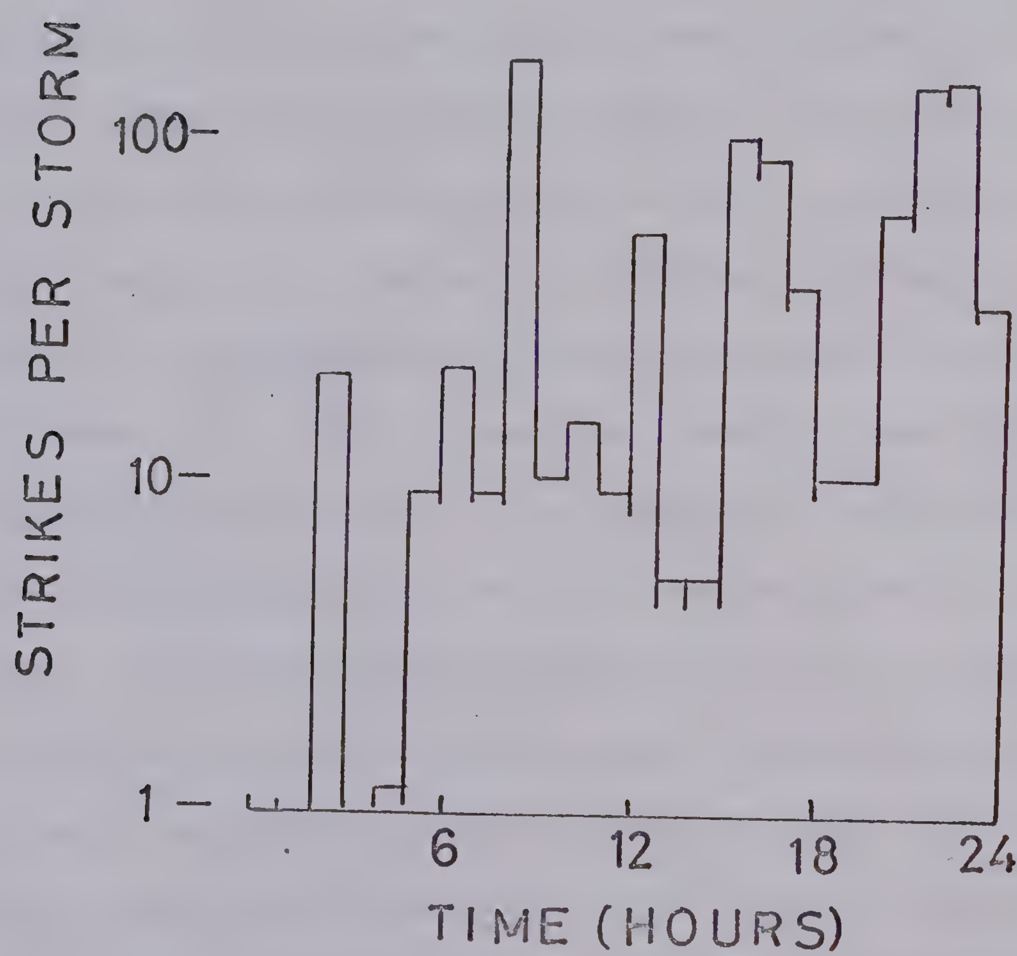


Figure 6.5 DIURNAL VARIATIONS IN THE AVERAGE NUMBER OF CLOUD-TO-GROUND FLASHES PER STORM.

Figure 6.5 shows diurnal variations in the average number of

cloud-to-ground flashes per storm. Three maxima exceeding 100 strikes per storm exist. The earliest maximum occurs between 0800 and 0900 MST, and the last maximum between 2100 and 2300 MST. The small average number of strikes per storm on either side of the 0900 maximum suggests that this maximum may result from biases in observing techniques. The maximum between 1500-1700 occurs during that part of the afternoon when instability in the atmosphere would be maximum and vertical motions within thunderstorms would be the greatest. As a result charge separation within these storms would be rapid and cloud-to-ground discharges profuse.

6.4 DISCHARGE RATES

The discharge rate is defined as the number of cloud-to-ground flashes occurring in an average five-minute interval. The spatial distribution of discharge rates is given in Figure 6.6. Three maxima exist, each with rates in excess of 3 flashes per 5 minutes. The most significant maximum occurs in the southwestern Edson Forest over rugged terrain. The relative maximum in the central Slave Lake Forest is associated with the maximum present in Figure 6.4 as is the maximum at Bitumont (BM).

Based on the assumption that the structure and stage of thunderstorm development can be deduced from discharge rates, we can infer several characteristics of Alberta thunderstorms. It is generally accepted that charge centers within thunderstorms are best developed during the mature stage of the storm's life cycle. Consequently high discharge rates would imply that storms on the average were in the mature stages of development. Following this premise, the results indicated in Figure 6.6 suggest that on the average thunderstorms over the northwestern parts of the province are poorly organized, existing in

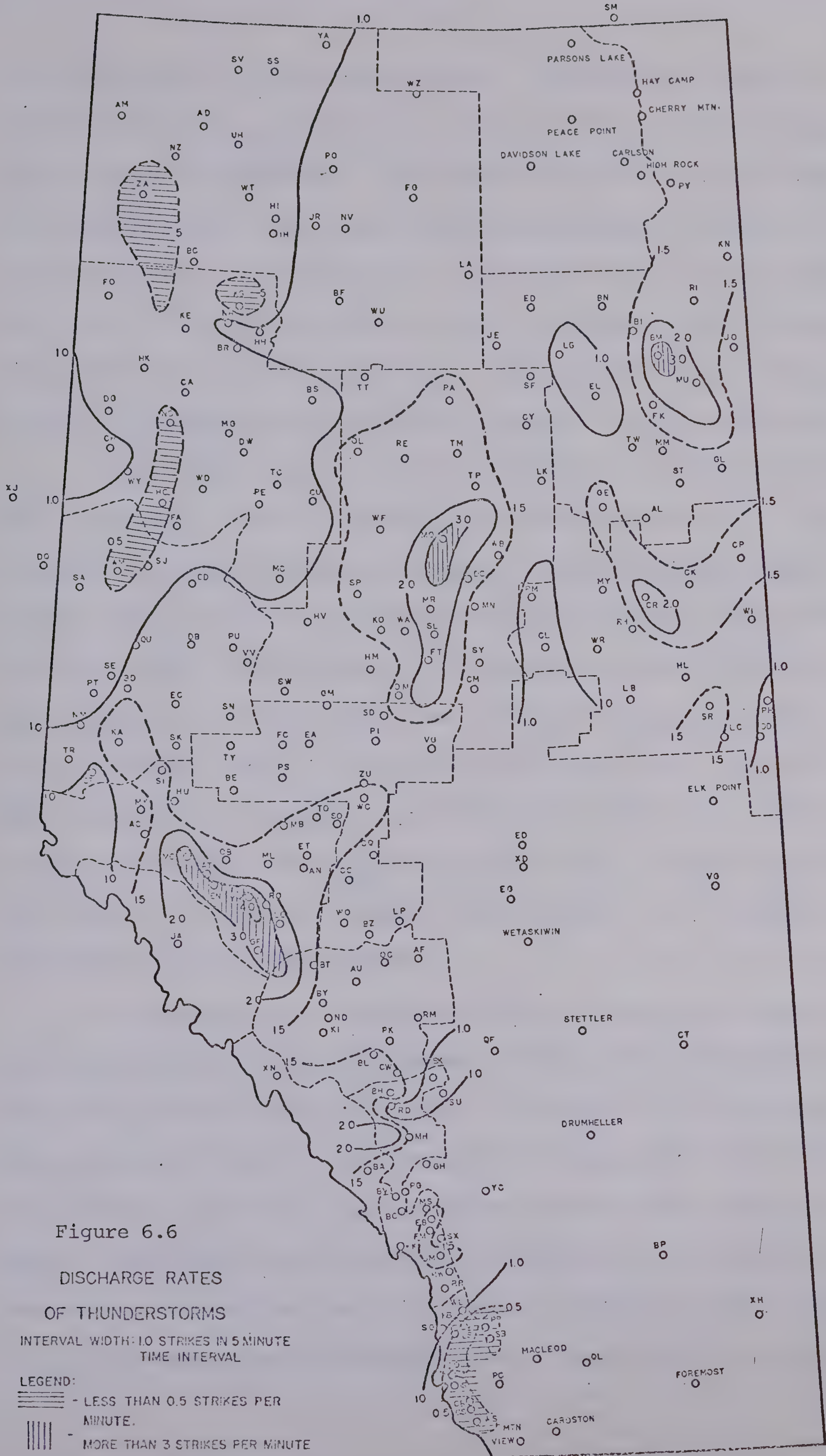


Figure 6.6

DISCHARGE RATES

OF THUNDERSTORMS

INTERVAL WIDTH: 1.0 STRIKES IN 5 MINUTE TIME INTERVAL

LEGEND:

- LESS THAN 0.5 STRIKES PER MINUTE.
- MORE THAN 3 STRIKES PER MINUTE
- INTERMEDIATE CONTOURS FOR DISCHARGE RATES

either the cumulus or dissipative stages. Thunderstorms present in Central Alberta will on the average exist in the mature, electrically active stages of development. The frequent burns in the past 30 years delineated on forest cover maps confirm that devastating effects are associated with the high discharge rates present in the central Slave Lake Forest. The gradient present in the isopleths of equal discharge rates just to the west of Bitumont (BM) indicates that storms mature as they move eastward from the southern slopes of the Birch Mountains.

The maximum appears to be the result of the elevation-discharge rate correlation listed in Appendix D for elevated forests. The 0.34 correlation coefficient between discharge rates and station elevations suggests that the thunderstorms over the rugged terrain of the southern forests discharge very frequently. The physical processes leading to this relation can be recognized if we consider a thunderstorm moving toward a mountain peak. If the height of the base of the cloud remains constant, the potential gradient in the sub-cloud layer must intensify as the storm moves towards higher terrain. The resultant intensification of the potential gradient initiates many more cloud-to-ground discharges over mountainous terrain.

The assumption of a constant height cloud base and constant vertical currents as the storm approaches a mountain will not always hold. The increased buoyant forces the cloud will encounter as it moves over the mountain will serve to raise the height of the cloud's base, intensify vertical velocities in the cloud and increase charge separation. However, the effect schematically shown in Figure 6.7 will still be important in intensifying sub-cloud potential gradients in the mountains.

The ambient earth-ionosphere gradient appears to have only a

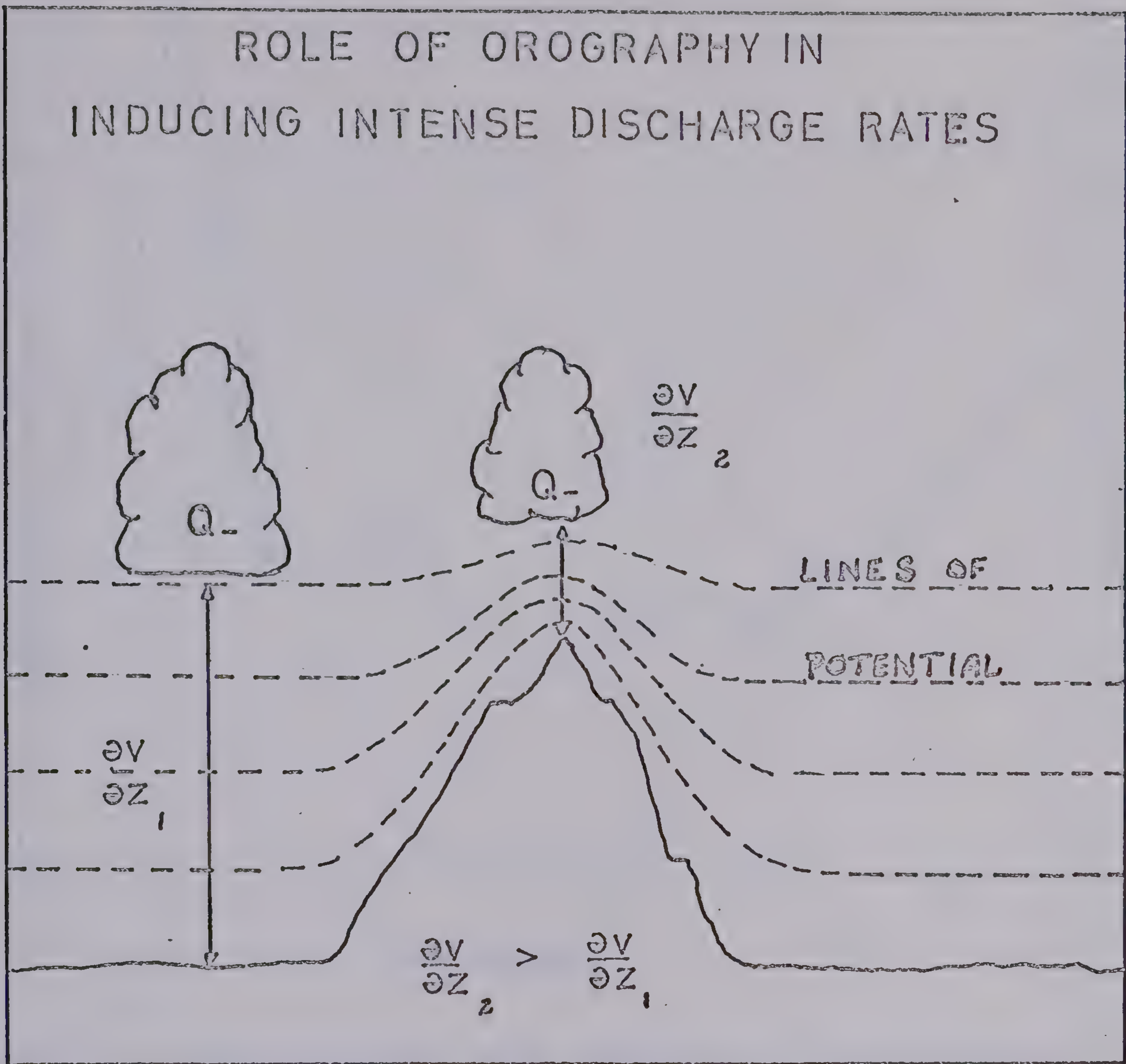


Figure 6.7 THE EFFECT OF A MOUNTAIN ON THE POTENTIAL GRADIENT $\partial V/\partial z$ IN THE SUB-CLOUD LAYER. Although the charge Q may remain constant $(\partial V/\partial z)_2 > (\partial V/\partial z)_1$.

minor effect on discharge rates as Figure 6.8 indicates. Although the maximum which occurs between 2000 and 2200 MST is duplicated in the graph of discharge rates the mid-morning potential gradient maximum is not. The peak discharge rates observed in storms between 0200 and 0300 MST suggests that nocturnal thunderstorms are very active. Part of this

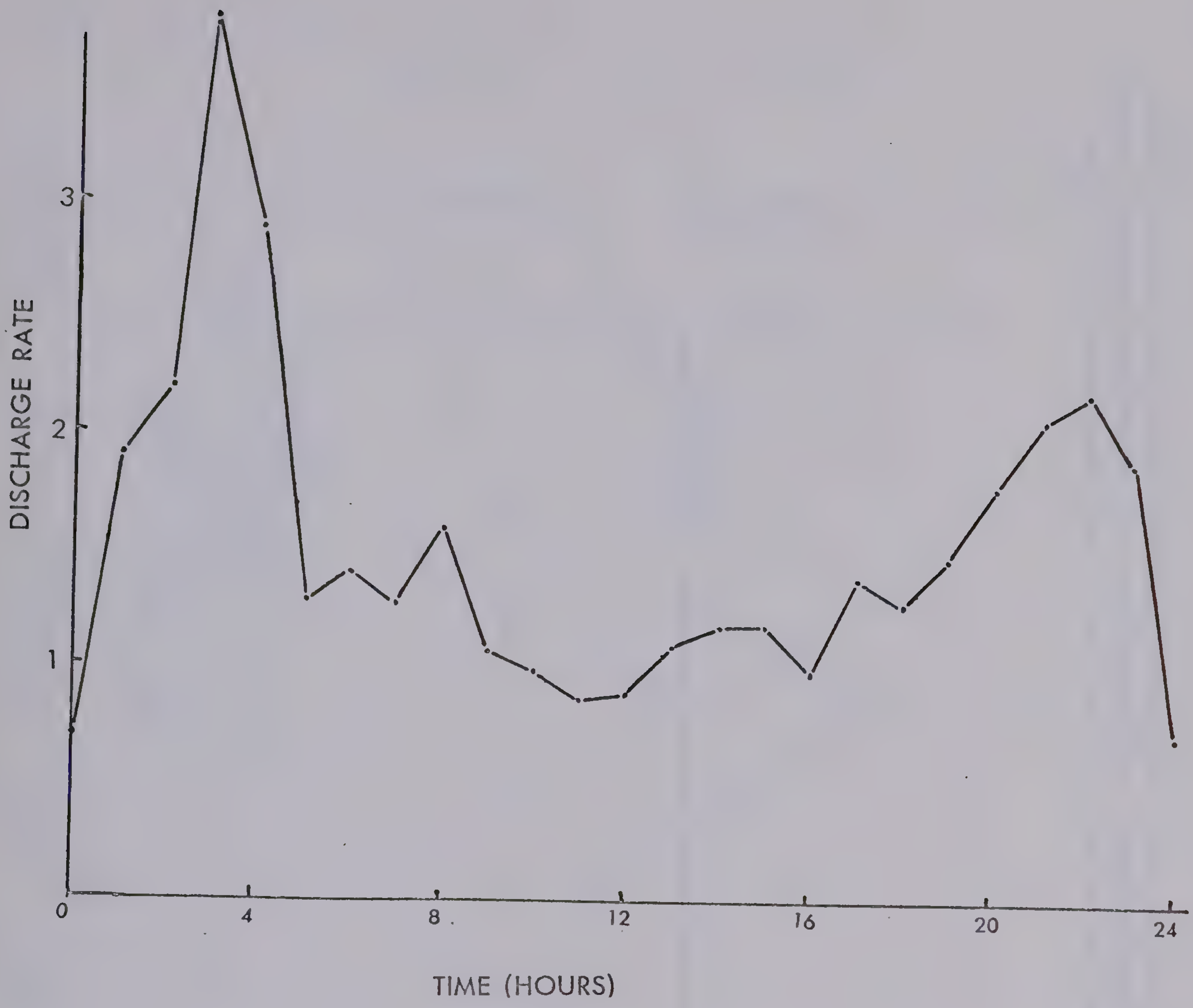


Figure 6.8 DIURNAL VARIATIONS IN THE DISCHARGE RATE OF THUNDERSTORMS.

maximum can be attributed to observer bias. Because only those storms active enough to awake the observer will be watched, high counts of cloud-to-ground discharges seem likely. Generally a half-awake observer is not the most accurate lightning counter.

Both the AEH and the ALR techniques were applied to learn the effects of topography and orography on the electrical character of thunderstorms. The results of the application of the AEH technique shown in Figure 6.9 reflect a tendency for thunderstorms with high

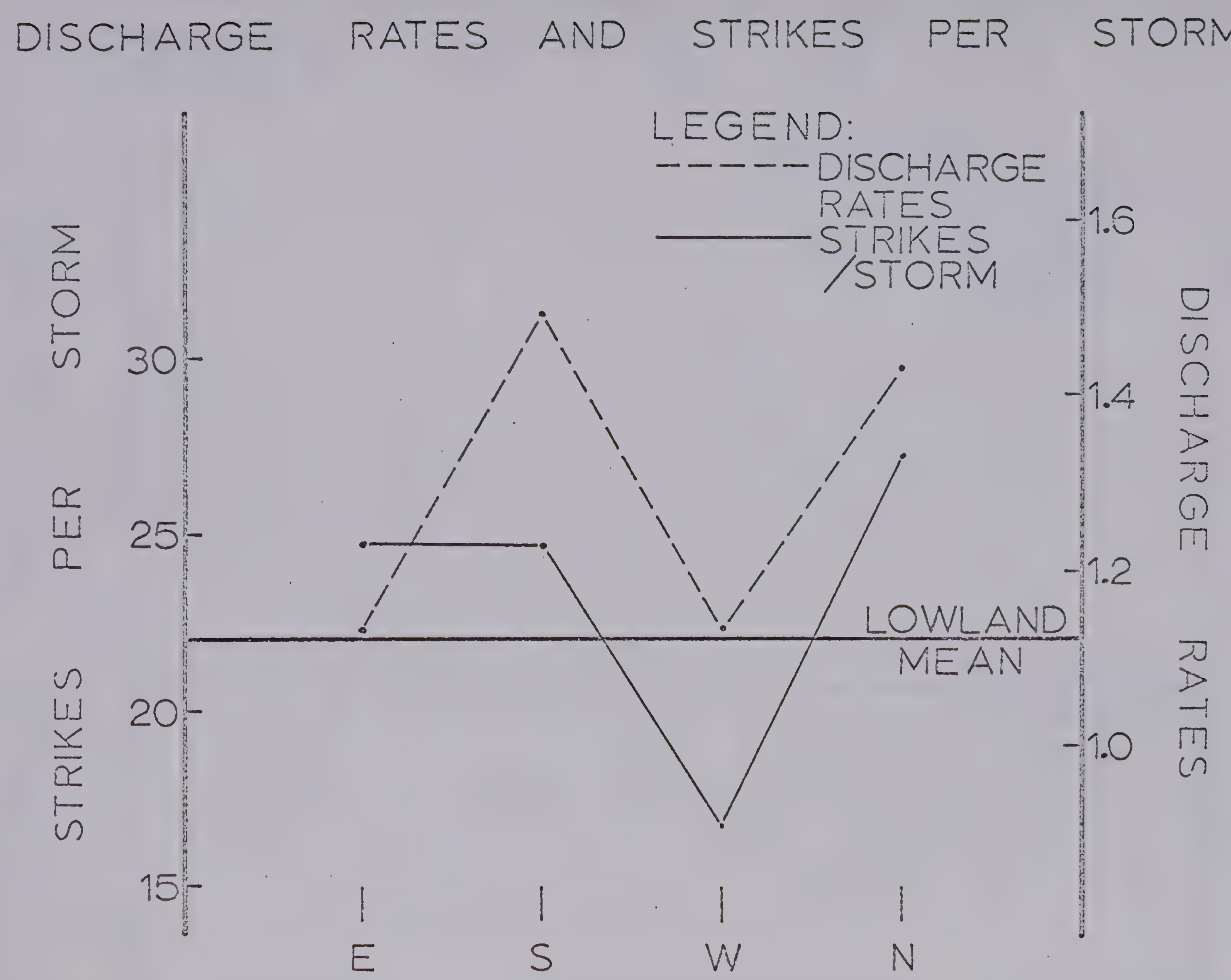


Figure 6.9 ASPECT DEPENDENT VARIATIONS IN THE DISCHARGE RATES AND TOTAL NUMBER OF STRIKES ASSOCIATED WITH EACH THUNDERSTORM. The horizontal line represents the mean values for storms occurring over the lowland forests. The aspect of the slope is given along the abscissa.

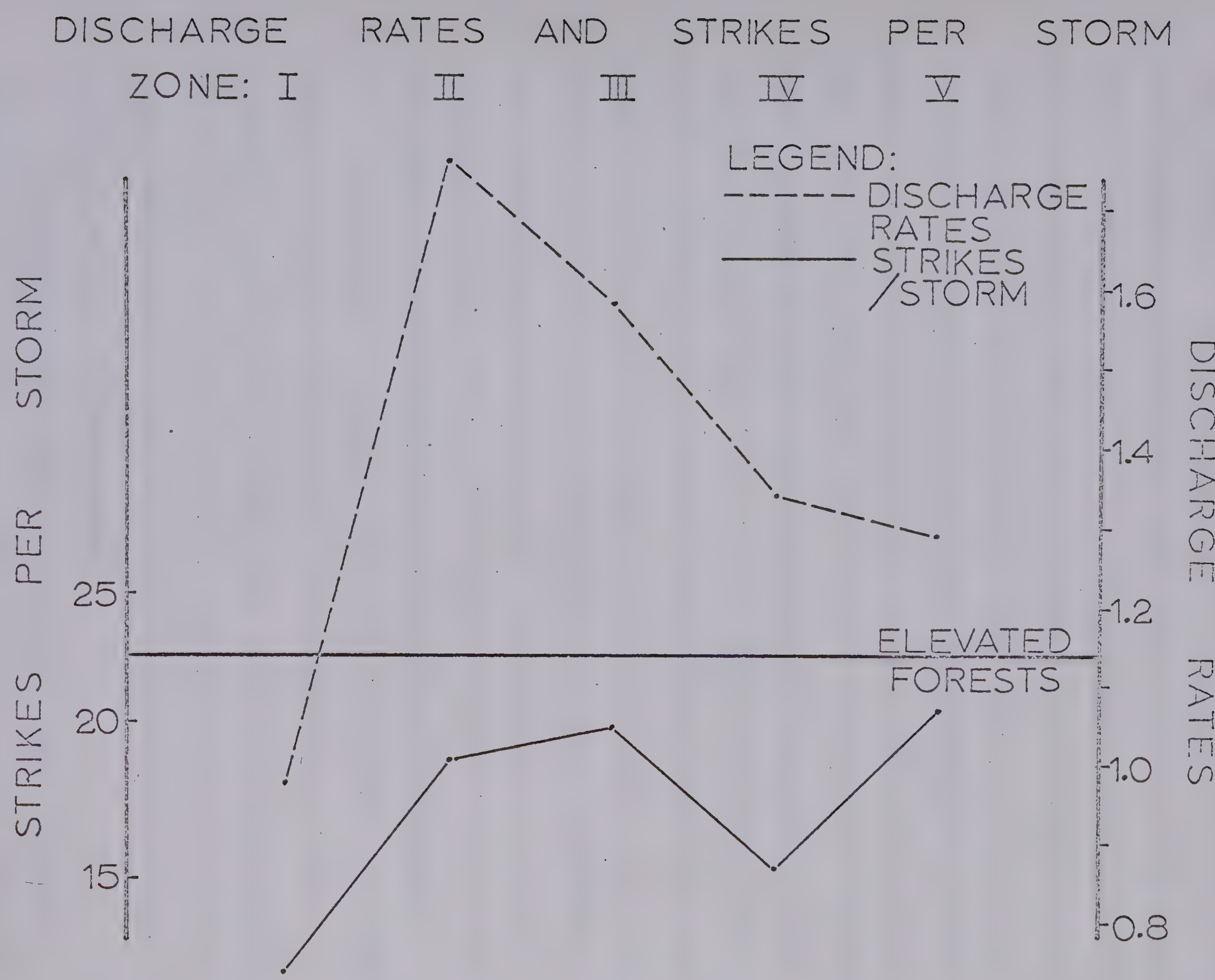


Figure 6.10 VARIATIONS IN THE DISCHARGE RATES AND NUMBER OF DISCHARGES FOR LIGHTNING STORMS OCCURRING IN THE LEE OF THE CONTINENTAL DIVIDE. The horizontal line represents the mean for the elevated forests.

discharge rates to form either to the north or to the south of topographical features. The low discharge rates and mean number of flashes per storm characterizing thunderstorms observed over western slopes suggests that such storms are poorly organized, being either in their formative or dissipative stages. It was shown in Chapter 4 that thunderstorms over western slopes have short durations and occur relatively late in the afternoon. This suggests that their apparent disorganization is the result of dissipative forces which are destroying the cloud's circulation. The low discharge rates associated with thunderstorms on eastern slopes indicates that these storms are also poorly organized, but probably for a different reason than are west-slope storms. The early onset times characterizing storms over eastern slopes suggest that these clouds are evolving into the mature stage of development. Thunderclouds occurring over northern and southern slopes have both high discharge rates and high mean flashes per storm. These high values imply that north-facing and south-facing slopes experience thunderstorms which are well-organized and probably in their mature stages of development.

The effects of orography on the electrical activity of thunderstorms is summarized in Figure 6.10. The increase in the number of flashes per storm in zone 5 suggests that thunderstorms are developing into maturity as they move into zone 5. The maximum in zones 2 and 3 suggests that the mesoscale wave assists in organizing the physical and electrical structure of thunderstorms.

The high discharge rates in zones 2 and 3 can be partially attributed to the rugged terrain present in these zones. Over zone 1 thunderstorms do not have high discharge rates which suggests that the mesoscale wave suppresses cloud development by dissipating cumulonimbus

clouds before they reach their full potential to produce lightning.

Over the lowland forests the discharge rates are related to station elevations by a correlation coefficient of -0.28 and to station longitudes by a coefficient of -0.39. Both of these correlations suggest that thunderstorms over the lower terrain in the more eastern part of the province are more active than those in the west. These correlations support the earlier model which suggested that storms formed over hills in the western lowland forests with the organized thunderstorms visible to observers situated farther to the east. Because air mass thunderstorms would likely be more infrequent over lower terrain due to the absence of trigger mechanisms these results suggest that the thunderstorms initiated by synoptic features such as fronts are more electrically active than air mass storms. The 0.30 correlation coefficient which relates initial bearings to discharge rates suggests that storms approaching from the west or northwest have the greatest electrical activity. Because storms moving into a particular lookout from the west are more likely to be in the mature stage of development than are storms forming to the southeast of that station, this correlation confirms our assumption about electrical activity and storm development.

6.5 THE CHARACTER OF LIGHTNING STRIKES

Alberta Forest Service personnel classify lightning into three categories based on the intensity of precipitation associated with the storm (see Chapter 3). The dry strikes generated by thunderstorms which do not produce precipitation reaching the earth's surface are felt by foresters to be the cause of many fires. They feel that the absence of precipitation makes the strike more effective in initiating a fire.

The existence of the dry-strike storm appears to contradict some theories of contemporary meteorologists who believe precipitation must be present in the cloud before the charge necessary to produce a lightning strike will be generated. Although few explanations for the phenomenon have been forwarded, dry strikes are not unique to Alberta. In Arizona's northern forests the dry strikes which occur early in the season are hazardous to forests and foresters. Murray (1951) describes a very striking example of this phenomenon. It appears that these strikes are produced by developing cumulonimbus which approach mountain peaks and undergo the process described by Figure 6.7. Since precipitation processes do not predominate within these clouds, the dry strikes are likely produced by clouds whose bases are close to the mountain peak. Another source of dry strikes can be found in the high-based thunderstorm whose precipitation evaporates before reaching the ground.

Figure 6.11 shows the spatial distribution of the relative frequency of dry strikes. Three maxima, each associated with mountain peaks, appear in the southern forests. Other relative maxima indicate that at least 10 per cent of the storms occurring in the northwestern Slave Lake Forest and the western Peace River Forest produce only dry strikes. These rather localized maxima combined with the maxima at Keg River (KG), Thickwood (TW) and Ponton (PO) appear to be the result of thunderstorms which are either poorly organized or propagating in a very dry atmosphere.

Figure 6.12 displays the diurnal variations in the frequency of thunderstorms with dry strikes. From Figure 6.12 it appears that storms producing dry strikes alone occur early in the afternoon, most frequently between 1400 and 1500 MST. Most storms at this time of the

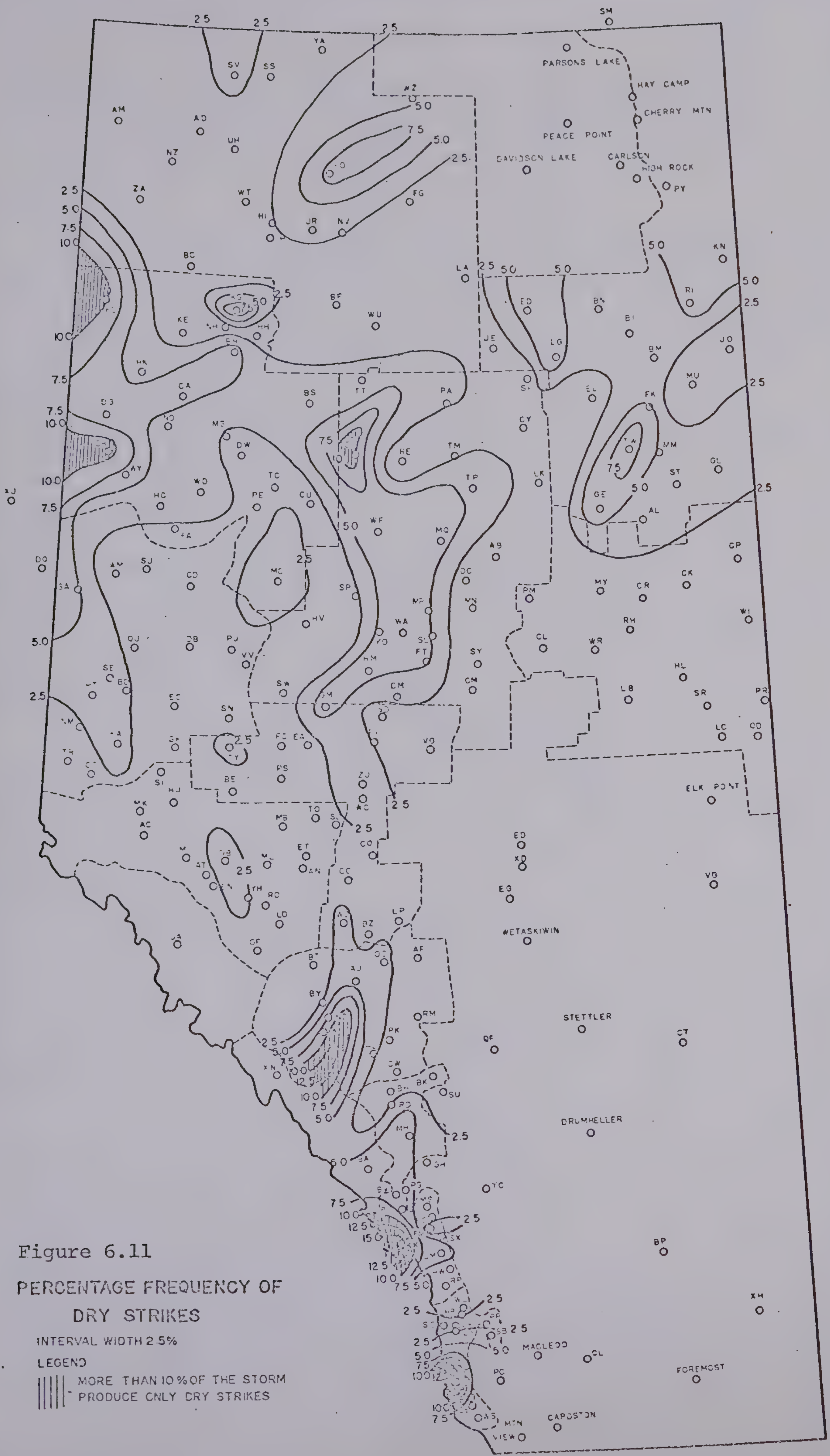


Figure 6.11

PERCENTAGE FREQUENCY OF DRY STRIKES

INTERVAL WIDTH 2.5%

LEGEND

MORE THAN 10% OF THE STORM PRODUCE ONLY DRY STRIKES

NUMBER OF DRY-STRIKE STORMS. (for the period from 1962-68)

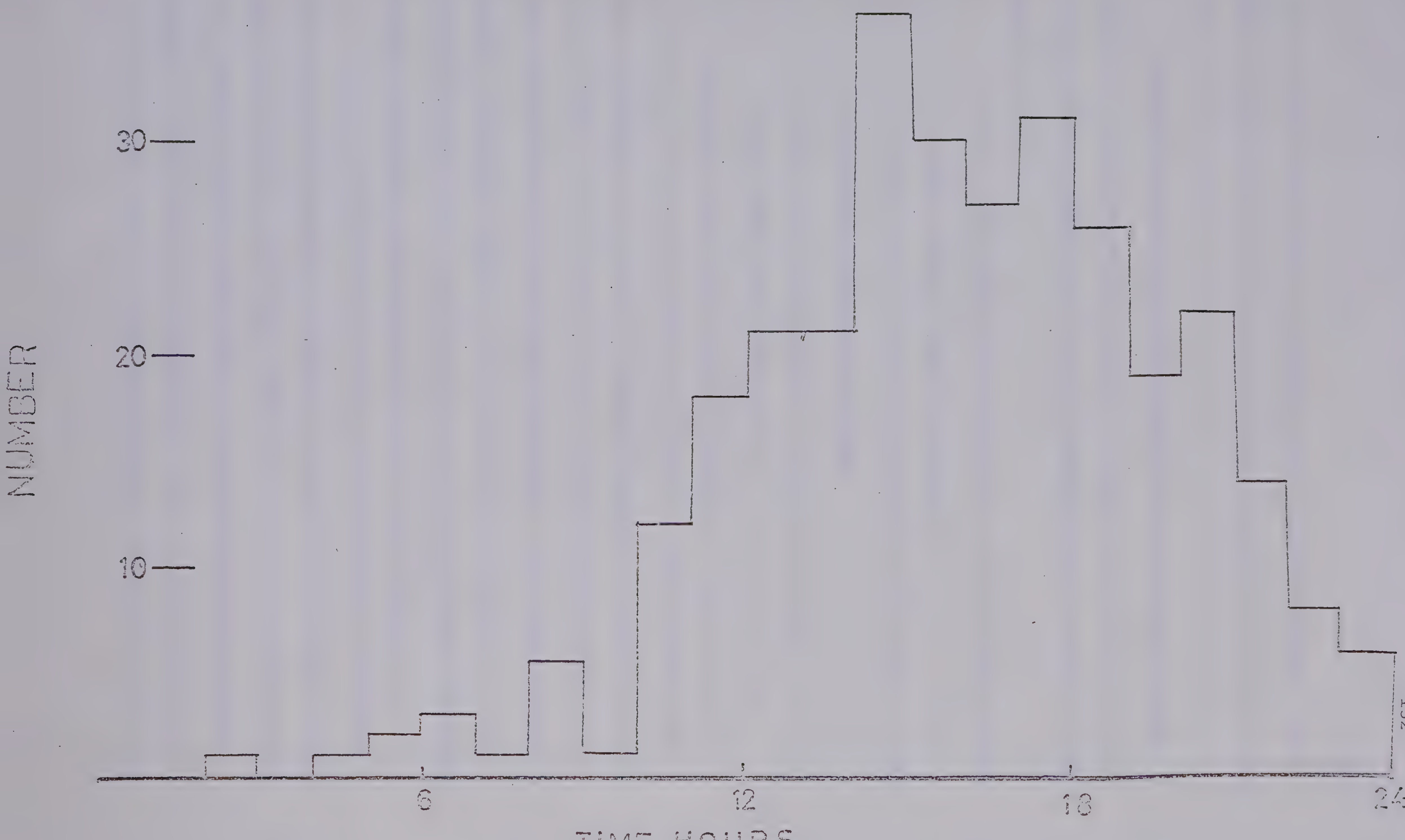


Figure 6.12 DIURNAL VARIATIONS IN THE NUMBER OF DRY-STRIKE STORMS.

day are in the cumulus stages of development. From this maximum, the frequency of dry-strike storms decreases to zero by 0000 MST on the following day.

Generalizing this inference relating storm development to the character of lightning strikes, subjective hypotheses (Rankine, 1881) can be set up to allow conclusions from the lightning characteristics. These hypotheses are:

1. that the dry-strike thunderstorm will be most probable during the early stages of storm development
2. that wet-strike storms will be observed when a storm is in its late mature or dissipative stages
3. that wet-dry-strike storms occur during the mature stages of the thunderstorm's life cycle.

Although the per cent relative frequency of thunderstorms with dry-strikes was not significantly correlated with either station location or elevation over lowland or elevated forests, this was not the case for wet-strike and wet-dry-strike storms over the lowland forests. Over the elevated forests the onset times are related to the relative frequency of dry-strike storms by a 0.33 correlation coefficient. This correlation implies that dry-strikes are generally associated with storms forming at stations characterized by late afternoon thunderstorms.

Over the elevated forests the relative frequencies of wet-dry-strike storms and wet-strike storms were related to the average number of flashes per storm by correlation coefficients of 0.41 and -0.29 respectively. These relations suggest that the thunderstorms over elevated forests in their dissipative stages do not produce as much lightning as do storms in their mature stages of development. The per cent relative

frequency of wet-dry-strike storms are related to storm durations by a 0.30 correlation coefficient which implies that mature thunderstorms are generally viewed for longer time intervals than dying thunderstorms are. Mature thunderstorms generally approach lookouts in elevated forests from the west or west-northwest as the 0.29 correlation coefficient relating the relative frequency of wet-dry-strike storms and initial bearings indicates.

Over the lowland forests the relative frequencies of wet- and wet-dry-strike storms are correlated with latitude by correlation coefficients of -0.36 and 0.36 respectively. These correlations suggest that wet-dry-strike storms are more frequent in the north while wet-strike storms occur more frequently in the southern lowland forests. The reason for this relation is obscure although the 0.46 correlation coefficient relating storm durations and the relative frequencies of wet-dry-strike storms provides a partial explanation. As thunderstorms over the northern forests can be observed for longer periods of time an observer located in the northern lowland forests is more likely to see a thunderstorm pass through its mature stage of development than is an observer in the southern lowland forests. This correlation could also imply that thunderstorms in the southern lowland forests produce more precipitation than storms in the northern forests. The -0.41 correlation coefficient relating the relative frequencies of wet-dry-strike thunderstorms to median dates suggests that wet-dry storms tend to occur earlier in the season. The fact that early season storms tend to produce both wet- and dry-strikes is a reflection of the tendency of storms to form in the northern parts of the lowland forests early in the season. During June and early July prior to the average median date for thunderstorm days over lowland forests

(July 11) thermal energy assists in the development and maintenance of thunderstorms. During this part of the season thermal energy will play a more important role in maintaining vertical updrafts than it will later in the season. It is possible that strong buoyant forces will be present in early-season thunderclouds which have low liquid water contents. Later in the season thunderstorms rely more heavily on the latent heat released from condensing water vapour for the energy to drive their vertical motions. Although the liquid water content may be lower, they are able to generate ample charge to produce lightning. The strong vertical currents in June and early July thunderstorms are very effective in separating this charge, and although surface precipitation may not be widespread, electrical activity may be substantial. The work of Paul (1967) supports this hypothesis. His results show that a larger proportion of August hailstorms produced large[1] hail than did June storms. This fact suggests that the conditions necessary for large hail growth are more frequently present in a larger proportion of August storms. As high liquid water contents are essential to the growth of large hailstones, it would appear that higher liquid water contents are more probable in August storms. As a result, August thunderstorms will derive much of their energy from condensing water vapour.

The AEH technique was applied to information about the character of lightning strikes and the results are shown in Figure 6.13. Dry-strike and wet-dry-strike storms are relatively infrequent over western slopes, suggesting that very few storms over these slopes are in their cumulus stage of development. The predominance of wet-strike storms over these

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1 large hail refers to hailstones which are walnut size or larger (Paul, 1967).

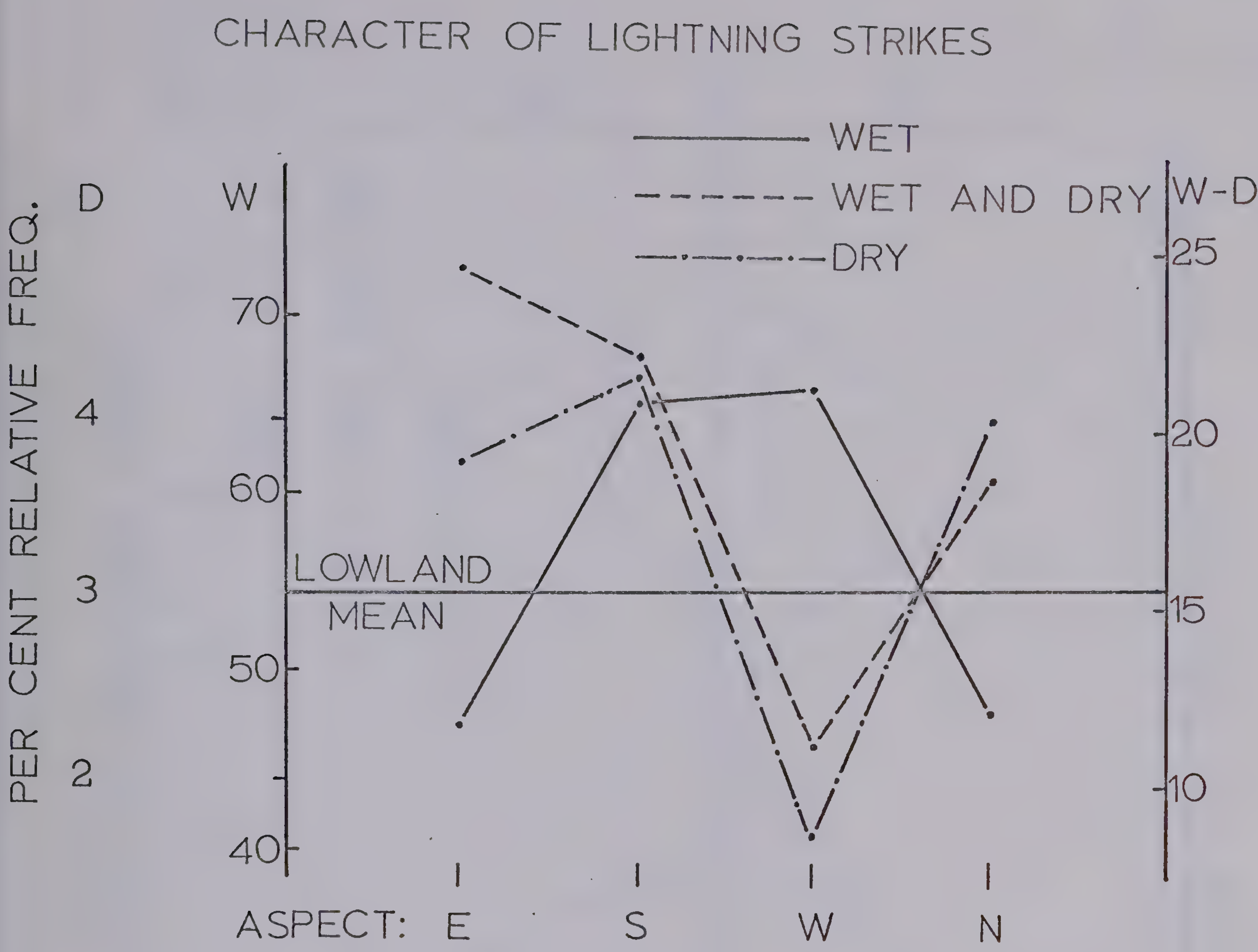

Figure 6.13 ASPECT DEPENDENT VARIATIONS IN THE CHARACTER OF LIGHTNING STRIKES. The horizontal line represents the mean values of the per cent relative frequencies of wet (W), dry (D), and wet-dry (W-D) strike storms over lowland forests. The aspect is given along the abscissa.

slopes implies that thunderstorms are in their dissipative stages. Over the eastern and southern slopes both dry-strike and wet-dry-strike storms are relatively frequent, suggesting that the thunderstorms over these slopes are in their cumulus and mature stages of development. This deduction implies that the southern and southeastern slopes are responsible for initiating thunderstorms. Over southern slopes only 12 per cent of the

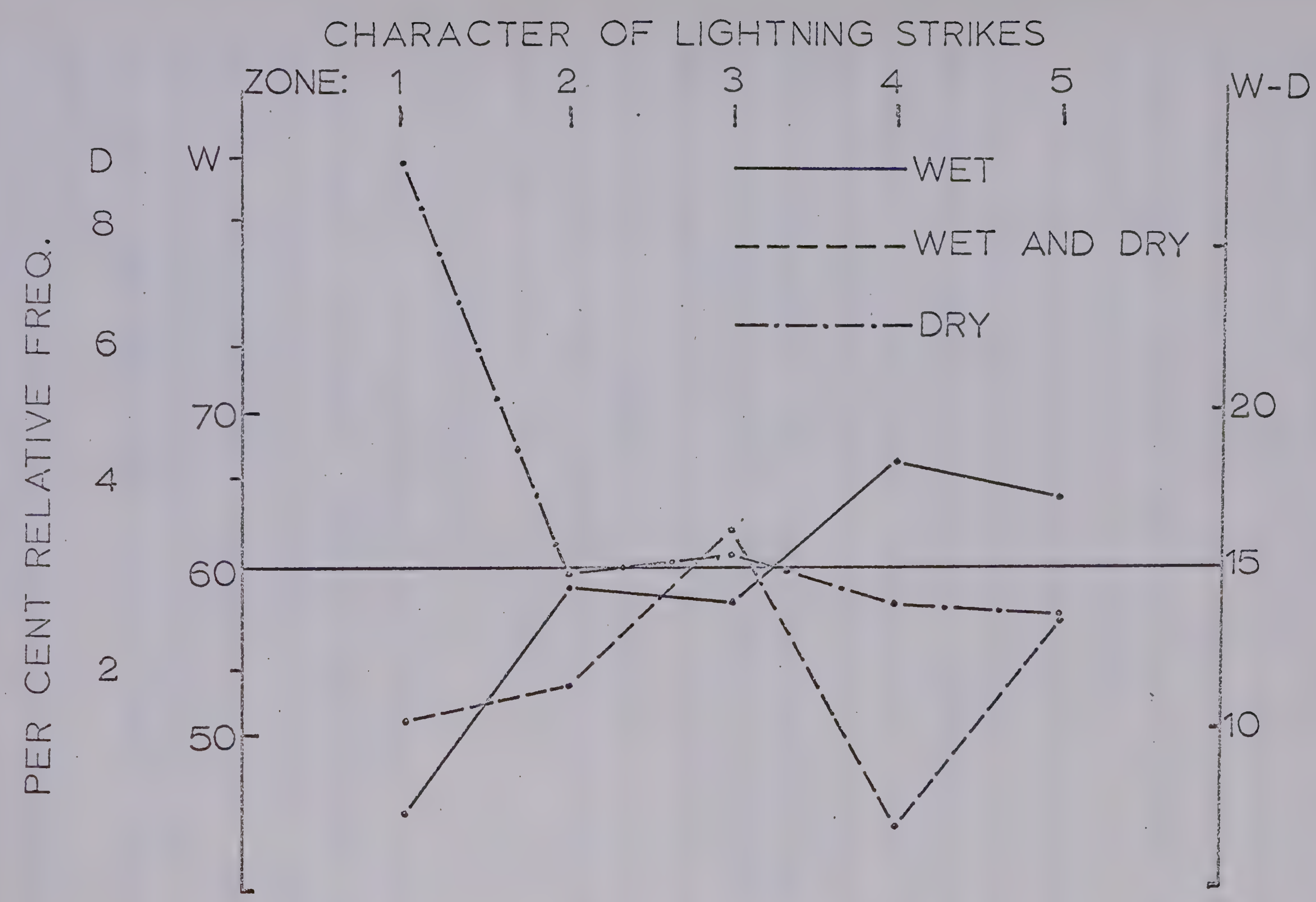

Figure 6.14 VARIATIONS IN THE CHARACTER OF LIGHTNING STRIKES IN THE LEE OF THE CONTINENTAL DIVIDE. The relative frequencies of wet (W), dry (D) and wet-dry (W-D) strikes are plotted against the zones used in the ALR technique.

storms produce lightning strikes of unknown character. This low relative frequency implies that thunderstorms occurring over southern slopes are easily seen. Earlier deductions which suggested that many of these storms will consist of one or two cells since they are in their formative stages explain why these storms are so open to view.

The application of the ALR technique to the characteristics of thunderstorm flashes uncovered two significant trends. The high relative frequency of dry-strike storms in zone 1 suggests that the mountains are responsible for initiating many dry-strike storms. Although the trend is not statistically significant the maximum in the relative frequency of wet-dry storms in zone 3 suggests that the mesoscale wave assists in initiating the propagating thunderstorms in their mature stages of development. The general increase in the relative frequency of wet storms east of the Continental Divide suggests that more thunderstorms dissipate as they move eastward into zones 4 and 5 than in zones 2 and 3. These results are summarized in Figure 6.14.

6.6 THE HAILSTORM-THUNDERSTORM RATIOS

The Hourly Data Summaries were used as the source of information for this aspect of the analysis. The map and graphs presented in this section are based on hourly observations taken at Fort Smith, Fort Saint John, Fort Nelson, Fort McMurray, Grande Prairie, Whitecourt, Edson, Namao, the Edmonton International Airport, the Edmonton Industrial Airport, Penhold, Rocky Mountain House, Coronation, Calgary, Lethbridge, and Medicine Hat.

Figure 6.15 shows the spatial distribution of the ratio of hours with hailstorms divided by hours with thunderstorms and multiplied by 1000. In an area south of Edmonton which includes Penhold and Calgary

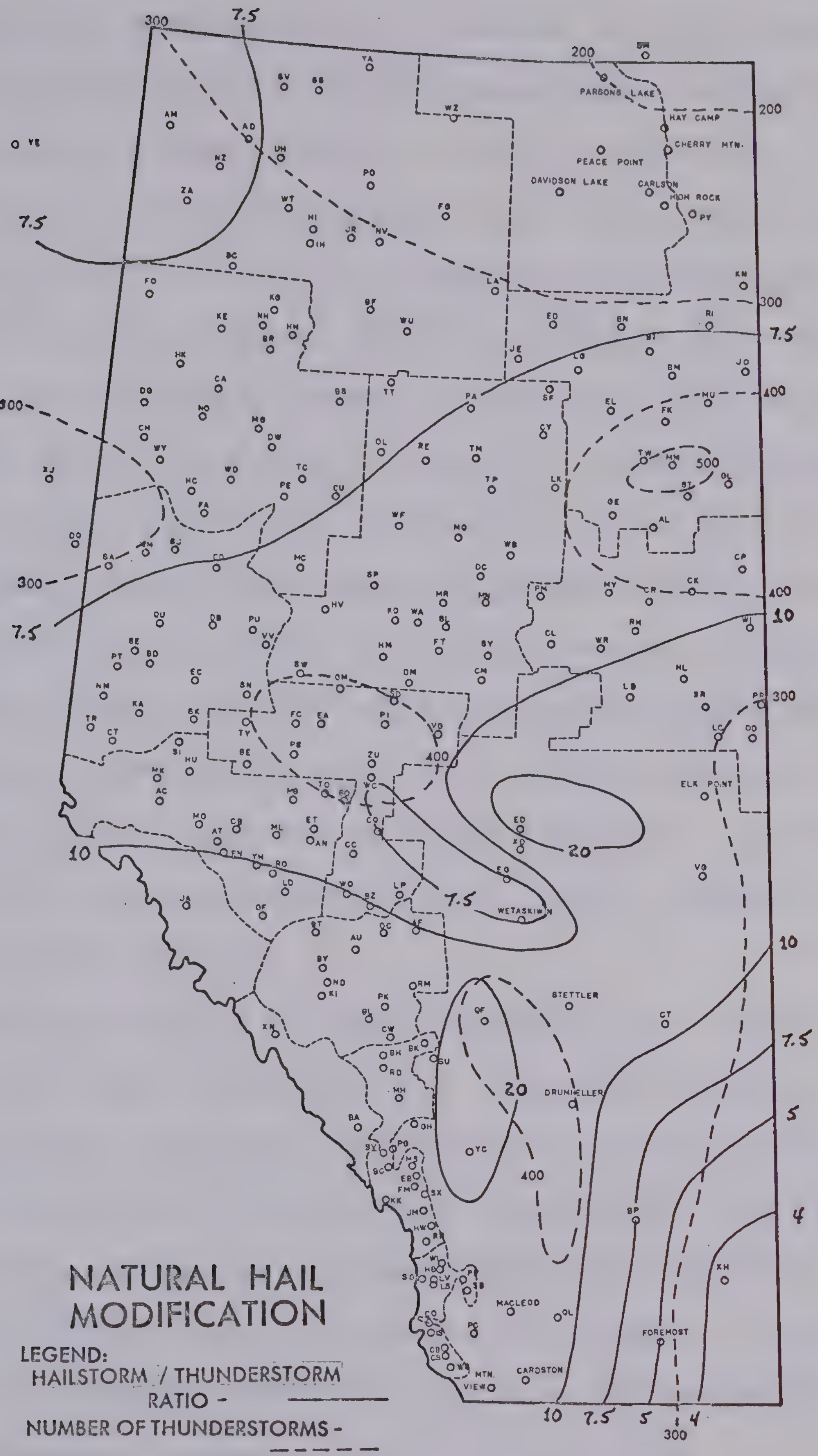

Figure 6.15 THE SPATIAL DISTRIBUTION OF H/T RATIOS AND THE NUMBER OF THUNDERSTORMS OCCURRING ON THE HOUR AT SYNOPTIC WEATHER STATIONS FOR A TEN-YEAR PERIOD.

maximum (hailstorm/thunderstorm) ratios are found. A similar maximum occurs at Namao. The H/T ratio increases between Rocky Mountain House and Penhold and then decreases farther to the east at Coronation. Low ratios are present in the southeastern portions of the province. The value of the H/T ratio decreases to the north over the lower terrain. The variation between the Edmonton International Airport (EG) and Namao (ED) is interesting as it demonstrates the large variations present in the H/T ratio over short distances. In general, the small H/T ratios occur over the lower terrain in the northern parts of the province. This distribution suggests that geographical features partially determine the nature of precipitation which a thunderstorm will produce.

Appleman (1960), who found high hailstorm/thunderstorm ratios over the higher terrain associated with the U.S. Rocky Mountains, suggests that a greater proportion of a given thundercloud over higher terrain is present above the freezing level. In this situation hail growth is more likely to occur.

Figure 6.16 shows the seasonal distribution of H/T ratios. The lowest ratios occur in July and August. Paul (1967) found that the relative frequencies of large hailstones were greatest for these two months. Thunderstorms which produce large hailstones require strong vertical currents. In July storms, the graupel particles which had formed in the cloud would melt before reaching the ground. It would appear that low ratios are linked to the height of the freezing level as well as geographical features.

Table 6.2 lists the ratios by hour. Paul (1967) stated that most of the large hail occurs between 1523 and 1822 MST. Table 6.2 shows that relatively large H/T ratios prevail during this time interval.

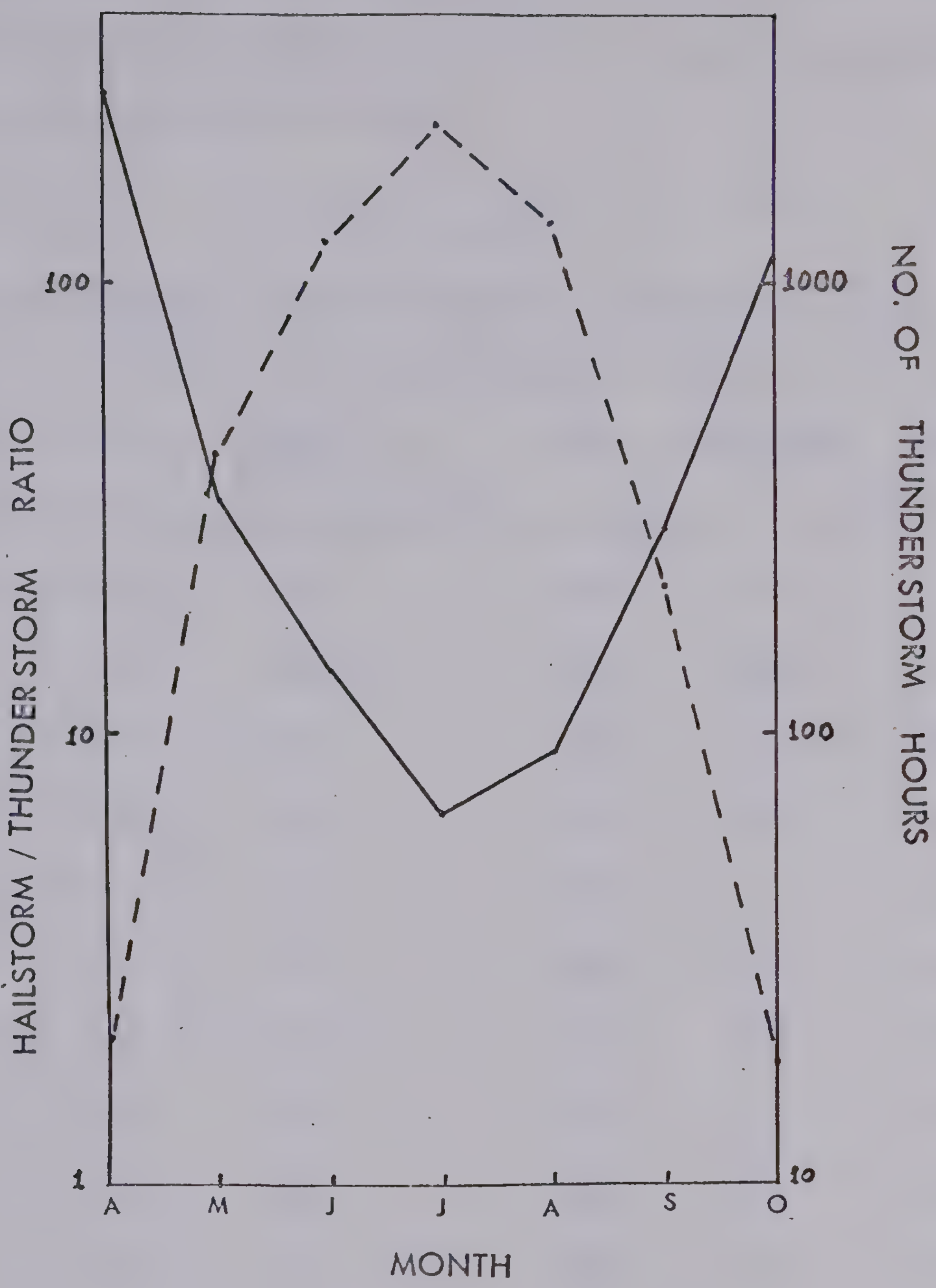

Figure 6.16 SEASONAL DISTRIBUTION OF HAILSTORM TO THUNDERSTORM RATIOS AND HOURS WITH THUNDERSTORMS. The solid line represents the H/T ratio for all stations while the broken line delineates the number of hours with thunderstorms for the same stations.

Thunderstorms which form after 1830 MST are less likely to have hail associated with them and any hail which does occur is likely to be shot or pea size (Paul, 1967).

These results suggest that geographical features may naturally modify hailstorms. The analysis of the temporal variations in the H/T

ratio suggests that the precipitation in mesoscale convection storms is dependent on the strength of the vertical motions within the cloud and the height of the freezing level.

TABLE 6.2

DIURNAL VARIATIONS IN THE HAILSTORM/THUNDERSTORM RATIO (X1000)

HOUR	H/T RATIO	FREQ. OF T HOURS	HOUR	H/T RATIO	FREQ. OF T HOURS
0100	4.7	218	1300	37.0	107
0200	0.0	188	1400	58.8	183
0300	0.0	174	1500	13.3	300
0400	0.0	127	1600	27.8	361
0500	10.3	97	1700	33.3	442
0600	0.0	87	1800	14.3	493
0700	0.0	75	1900	4.3	469
0800	0.0	70	2000	7.1	424
0900	0.0	49	2100	7.1	419
1000	0.0	38	2200	7.8	388
1100	22.7	44	2300	2.8	357
1200	52.5	58	2400	0.0	312

Russian hail modification experiments provide an explanation for the difference between hail and non-hail thunderstorms. Sulakvelidze (1965) suggests that hailstones grow in a high liquid water content region of the cloud known as the accumulation zone. This zone forms in every thunderstorm at the level where the speed of the updraft equals

the terminal velocity of falling droplets. The height of this zone relative to the freezing level determines the rate of growth and the final size of the hailstones. It has been noted in this study that thunderstorms with vigorous updrafts and bases not too far below the freezing level are most likely to produce hail. This effect combined with the smaller distances between the freezing level and the terrain, are responsible for the high H/T ratios present over the higher terrain in Figure 6.15. Pakiam and Maybank (1970) also found a reduction in the lightning activity associated with severe hailstorms.

A decrease in the annual frequencies of cloud-to-ground discharges can be seen in the Clearwater-Rocky Forest where high H/T ratios are also present. It would appear that the precipitation mechanisms generating charge distributions are necessary for intense electrical activity. The smaller distances between the freezing level and the ground reduce the melting the hailstone will undergo as it falls to the ground.

CHAPTER VII

CONCLUSIONS AND APPLICATIONS

... of making many books there is no end; (Eccl. 12:12)

7.1 INTRODUCTION

The words of the Preacher suggest that the writing of books is an endless task. It would appear from the recent flood of literature about thunderstorms that research and articles on the topic may never be ended, either. This study has provided a few generalizations regarding the formation of thunderstorms in Alberta and some maps which should be of value to foresters and forecasters concerned with the province of Alberta. It has not provided a complete solution to the forecasting problems mentioned in Chapter 1.

This chapter summarizes the implications of the results in the light of the objectives of the study mentioned in Section 1.5. Inferences from these results which could provide topics for further study are elaborated upon. The chapter concludes with some possible applications of some of the results contained in this thesis.

7.2 CONCLUSIONS REGARDING THUNDERSTORM CHARACTERISTICS

Although only short-term statistics were available, the stable patterns present in thunderstorm characteristics indicated that thunderstorms in many cases result from mesoscale phenomena associated with certain geographical features. Thunderstorms in the eastern part of the province appear earlier in the day than they do further to the west.

Nocturnal thunderstorms are most frequent near the Continental Divide in the southern forests although a few form in the northeastern forests. There are several locations where very frequent thunderstorm activity is evident. The areas in the southwestern Athabasca and the western Whitecourt Forests are most noteworthy. During the season thunderstorm activity shifts southward from the northern forests to the central and southern forests. Late-season thunderstorms develop over the rugged terrain present in the southern forests.

Cloud-to-ground lightning is most frequent in the Whitecourt, Slave Lake and Athabasca Forests. Most of the charge is transferred from the cloud to the ground between 1600 and 2100 MST. Discharge rates, which are an indicator of the electrical activity within a thunderstorm, are greatest to the lee of the Continental Divide, in the Edson Forest, and in the northeastern parts of the province. Dry-strike thunderstorms are most frequent in the early afternoon. Storms in the lee of the Continental Divide are most likely to produce only dry-strikes. The durable wet-dry storms tend to occur during the months of June and July. Hailstorm-to-thunderstorm ratios are highest over higher terrain. They reach minimum values during the month of July.

Thunderstorms over the Swan and Clear Hills were investigated. Early durable storms occur over the eastern slopes. Storms on the western and northern slopes occurred later in the day and dissipated more rapidly. Thunderstorms on the western slopes were generally wetter. Thunderstorms over southern and northern slopes have high discharge rates and western slopes experience fewer cloud-to-ground discharges than do other slopes.

Thunderstorm characteristics in the lee of the Continental Divide

exhibited a wave structure. Dry-strike storms appear most probable within 40 km of the Divide. Storms 40-80 km away have high discharge rates and are frequently located to the east of the lookout reporting them. Farther to the east of the Divide, thunderstorms commence later in the day and a larger proportion of the storms are wet-strike storms.

The probability that a thunderstorm will produce hail is a minimum over lower terrain. The thunderstorms which occur early in the season, late in the season, or between 1200 and 1900 MST are most likely to produce hail.

7.3 CONCLUSIONS RELATED TO CLIMATOLOGICAL PROCESSES

As a result of the foregoing conclusions, and a number of others embodied in the text, several climatic processes which control Alberta's convective activity were modelled. Radiation from the sun is responsible for the existence of preferred areas and times of convective development. The threshold energy hypothesis of thunderstorm development states that under known moisture, temperature and wind distributions a critical amount of energy must be supplied to the lower troposphere before thunderstorms will form. The seasonal distribution of thunderstorms over Alberta's forests is a product of this effect.

The role of topography in initiating storms can be inferred from the distribution of thunderstorm characteristics on the sides of a hill. Variations in the heating which occurs over slopes which face different directions result in strong early-afternoon thermals over the southern slopes. Cumulus congestus develop over these slopes, propagating through an atmosphere which has been modified by surface heating. Later in the afternoon cumulus form at the top of the intense thermals present on the

southwestern slopes. These thunderclouds develop into highly organized electrical storms as they travel over the hills' southern slopes.

Several orographic effects appear in the lee of the Continental Divide. A mesoscale wave phenomenon with a wavelength of 80-90 km appears to accentuate the growth of orogenic thunderclouds. As a thunderstorm or a potential thunderstorm moves towards higher terrain the potential gradient between the ground and the cloud's base intensifies. The rugged terrain present in the mountains initiates strong thermals which in turn intensify updrafts within the thunderstorm. The resultant increase of separation of charge and the intensification of potential gradients in the sub-cloud layer cause thunderstorms moving towards mountains to be characterized by high discharge rates and high probabilities of dry-strikes.

The probability of hail occurring with a thunderstorm is dependent on elevation of the underlying terrain and the month. This deduction supports the basic implication of this thesis, namely, that through their effects on the structure of meteorological fields and their tendency to organize circulations within cumulonimbus clouds, topographic and orographic effects play a major role in determining the behavior of thunderstorms in Alberta.

7.4 SUGGESTIONS FOR FUTURE RESEARCH

This study has uncovered a few factors involved in lightning-caused fires. Much more work should be done in determining the relevant importance of the character of the lightning strike, the type and aridity of the fuel, the effects of topography, the build-up and the spread indices. A climatic map delineating the probability that a lightning-caused fire will occur in a particular location on a given day would be of great

value to the forester.

The role of geographical features in organizing the low-level meteorological fields of moisture, temperature and wind should be studied. Although mesoscale perturbations have been inferred from thunderstorm characteristics in this study such inferences are a poor substitute for actual measurements. The role of heat and moisture fluxes appear to be parameters which need further investigation.

Although the cloud is in part the product of geographical factors the thundercloud evolves primarily in the troposphere. The meteorological parameters affecting thunderstorm growth should be examined in order to determine the best indicators of thunderstorm activity. The possible explanation of such a study was mentioned in Section 1.4. Another avenue which should be investigated because it may lead to better thunderstorm predictions involves the use of models such as the Penn State Parameterized Model of Cumulus Convection (Weinstein and Davis, 1968). The rates and extends of growth such a model would experience in various meteorological fields could provide interesting information regarding the effects of various meteorological parameters.

Consumer-orientated research which first determines the user's needs and then attempts to provide a solution to the existing problems should be encouraged at both the academic and operational levels. Such studies not only are rewarding to the researcher but they do much to increase the public image of Meteorology in our society.

7.5 APPLICATIONS OF THE RESULTS

Frequently studies realize only partial success. The efforts involved in much of the work is not in vain, however, because the

intermediate results and techniques can be almost as valuable as the complete solution itself. These results have, in the main, satisfied the initial objectives. The maps used to display these results, and presented in this dissertation can be useful to both the forester and the forecaster.

For the forester the maps included in this analysis are of use because they provide information regarding the average areal distribution of and the expected times of occurrence of thunderstorm activity. This information allows aircraft and personnel to be moved from one threat area to another as the day or season progresses. The seasonal distribution of thunderstorms is a useful factor in scheduling the opening and closing dates of lookouts in various localities. The areas subjected to frequent cloud-to-ground discharges which were provided by charts in Chapter 6 should be considered when new lookouts are being constructed. The knowledge regarding source regions of thunderstorm development which has been presented in this thesis should be used to assist in decision making regarding the location of new lookouts and weather stations.

The forecaster can also derive benefits by using these charts. They provide information regarding the expected onset times of thunderstorms, the probable areas of thunderstorm occurrence, the affects of topography and orography on storm development, the seasonal distributions of thunderstorms and the geographical variations in the severity of electrical activity associated with storms, all facts which can be incorporated into a forecast. The charts showing the monthly probabilities of storm development in various localities provide a basis for comparative forecast verification techniques.

The meteorologist interested in studying lightning in Alberta would find use for the charts presented in Chapter 6. Studies set up in areas where lightning frequently occurred would be most likely to produce results. Those interested in cloud seeding experiments and hail modification are provided with information regarding the preferred areas of thunderstorm development and the probabilities that these storms will produce hail. This information should be used in determining the areas where cloud seeding is most needed.

Many other applications will become evident to individual users. The usefulness of the research depends, as all other research depends, on the user's readiness to evaluate and modify his operations in light of its implications.

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APPENDIX A

In order to discover some of the factors other than lightning itself, which characterize lightning-caused forest fires, the relationships between such fires and other geographical and meteorological variables are considered. Controversy has recently centered on the subject of the most effective ways to detect lightning-caused forest fires and forest fires in general. Table A.1 lists the discovery agents responsible for detecting lightning-caused fires.

TABLE A.1

AGENTS DISCOVERING LIGHTNING-CAUSED FOREST FIRES

AGENCY	NUMBER OF LIGHTNING-CAUSED FIRES REPORTED	RELATIVE FREQUENCY OF TOTAL NO. OF FIRES REPORTED (per cent)
Lookout operator	813	57.7
Forestry officer	64	4.6
Other forestry personnel	11	.8
Forest Service aircraft	250	17.7
Other aircraft	141	10.0
Industrial employees in forests	38	2.7
Public	74	5.2
Other government agencies	7	.5
Others	11	.8
Total	1409	100.0

With the foregoing distribution of detected lightning fires, the fires had grown to the sizes listed in Table A.2 prior to being detected.

TABLE A.2

SIZE TO WHICH LIGHTNING-CAUSED FIRES GROW PRIOR TO DETECTION

SIZE OF FIRE (ACRES)	NUMBER OF L-C FIRES REPORTED	RELATIVE FREQUENCY OF L-C FIRES REPORTED (per cent)
< 0.25	785	55.8
0.26 - 10	401	28.4
11 - 100	125	8.9
101 - 500	45	3.2
> 501	53	3.7
TOTAL	1409	100.0

In many cases the character of the topography around the location where the fire started, was reported. Based on a subjective evaluation of the topography the following distribution was found.

TABLE A.3

TYPE OF TOPOGRAPHY IN AREA WHERE LIGHTNING-CAUSED FIRES OCCUR

TERRAIN	NUMBER OF L-C FIRES REPORTED	RELATIVE FREQUENCY OF L-C FIRES REPORTED (per cent)
LEVEL	359	45.3
ROLLING	390	49.2
MOUNTAINOUS	43	5.5
TOTAL	792	100.0

In general lightning-caused fires occur in drier fuels. Table A.4 gives the number of fires initiated in four types of fuels for the cases where it was reported.

TABLE A.4

MOISTURE IN THE FUEL IN WHICH LIGHTNING-CAUSED FIRES COMMENCE

MOISTURE IN THE DUFF	NUMBER OF L-C FIRES	RELATIVE FREQUENCY OF L-C FIRES (per cent)
WET	71	23.1
DAMP	44	14.3
DRY	92	30.0
VERY DRY	100	32.6
TOTAL	307	100.0

The mean build-up index in the vicinity of lightning-caused fires is 42.6 and the mean spread index is 11.7.

At the time of the first prevention action, lightning-caused forest fires are generally moving slowly. This tendency is shown in Table A.5.

TABLE A.5

RATE AT WHICH FIRE-FRONT WAS SPREADING AT TIME OF INITIAL ATTACK

RATE OF ADVANCE	NUMBER OF L-C FIRES	RELATIVE FREQUENCY OF L-C FIRES (per cent)
< 2 ft./hr.	152	53.4
2 - 600 ft./hr.	100	35.0
> 600 ft./hr.	20	7.0
Wind borne sparks	4	1.4
Blowup	9	3.2
TOTAL	285	100.0

The relative frequencies of lightning-caused forest fires initiated in various vegetation covers are given in Table A.6.

TABLE A.6

COVER TYPE WHERE THE FIRE STARTED

COVER TYPE	NUMBER OF L-C FIRES	REL. FREQ. OF L-C FIRES (per cent)
SPRUCE	129	46.3
PINE	40	14.3
DECIDUOUS	39	14.0
MUSKEG	52	18.6
BOG	7	2.5
BRUSH	10	3.6
GRASS	2	.7
RECENT BURNS	0	0
CLEAR CUTS	0	0
OTHERS	0	0
TOTAL	279	100.0

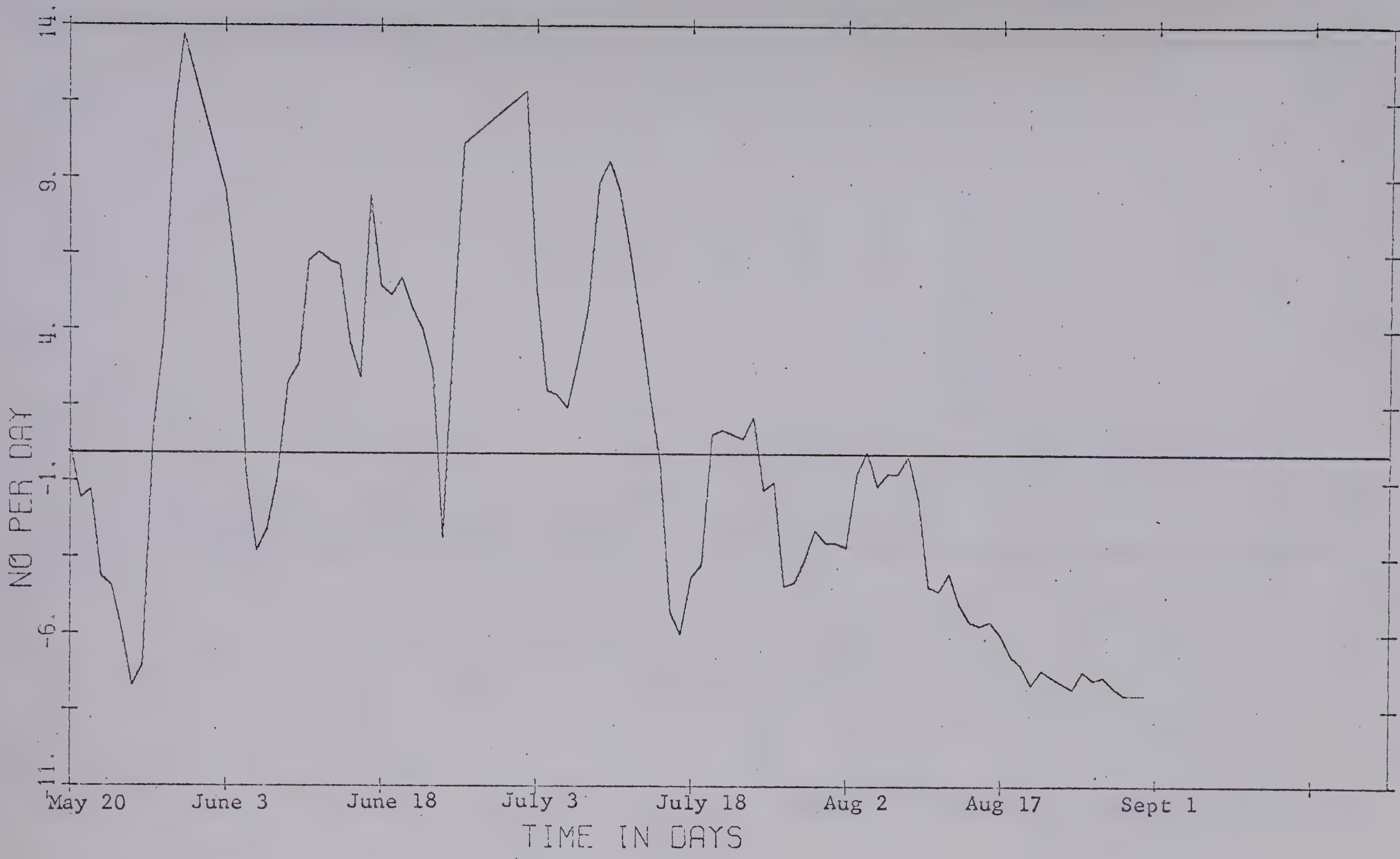
In 25 per cent of the cases timber is burning when action is first initiated against the fire. Table A.7 gives a list of the relative frequency of fires in the various types of fuels.

TABLE A.7

PRIMARY FUEL BURNING AT THE TIME OF THE INITIAL ATTACK

FUEL BURNING AT THE ORIGIN	FREQ. OF L-C FIRES REPORTED	REL. FREQ. OF FIRES REPORTED (per cent)
TIMBER	83	25.6
GRASS	39	12.0
BRUSH	7	2.2
SLASH	22	6.8
SNAGS	5	1.5
DOWNED LOGS	26	8.0
PEAT and DUFF	25	7.7
LICHEN	3	.9
MOSS	71	21.8
OTHERS	44	13.5
TOTAL	325	100.0

The seasonal distributions of both the lightning-caused fires and the mean daily onset times of lightning-caused fires were tabulated. The resultant series were passed through a symmetrical triangular with a width of seven days. Figures A.1 and A.2 show the results of this analysis. Figure A.1 shows that lightning-caused fires are very frequent between May 20 and September 1. With the exception of two small broad peaks the curve decreases subsequent to July 14. The mean daily onset times of lightning-caused fires have some periodicity as Figure A.2 demonstrates. Although these cyclic variations appear to be real, lightning-caused fire onset times do not exhibit a seasonal trend.



SMØØTHED FREQUENCY ØF LIGHTNING FIRE ØCCURRENCE

Figure A.1 THE SMOOTHED SEASONAL DISTRIBUTION OF LIGHTNING-CAUSED FIRES. The plot commences on May 20 and concludes on September 1. The number of fires per day with the seasonal average of 10.0 extracted is plotted along the ordinate.

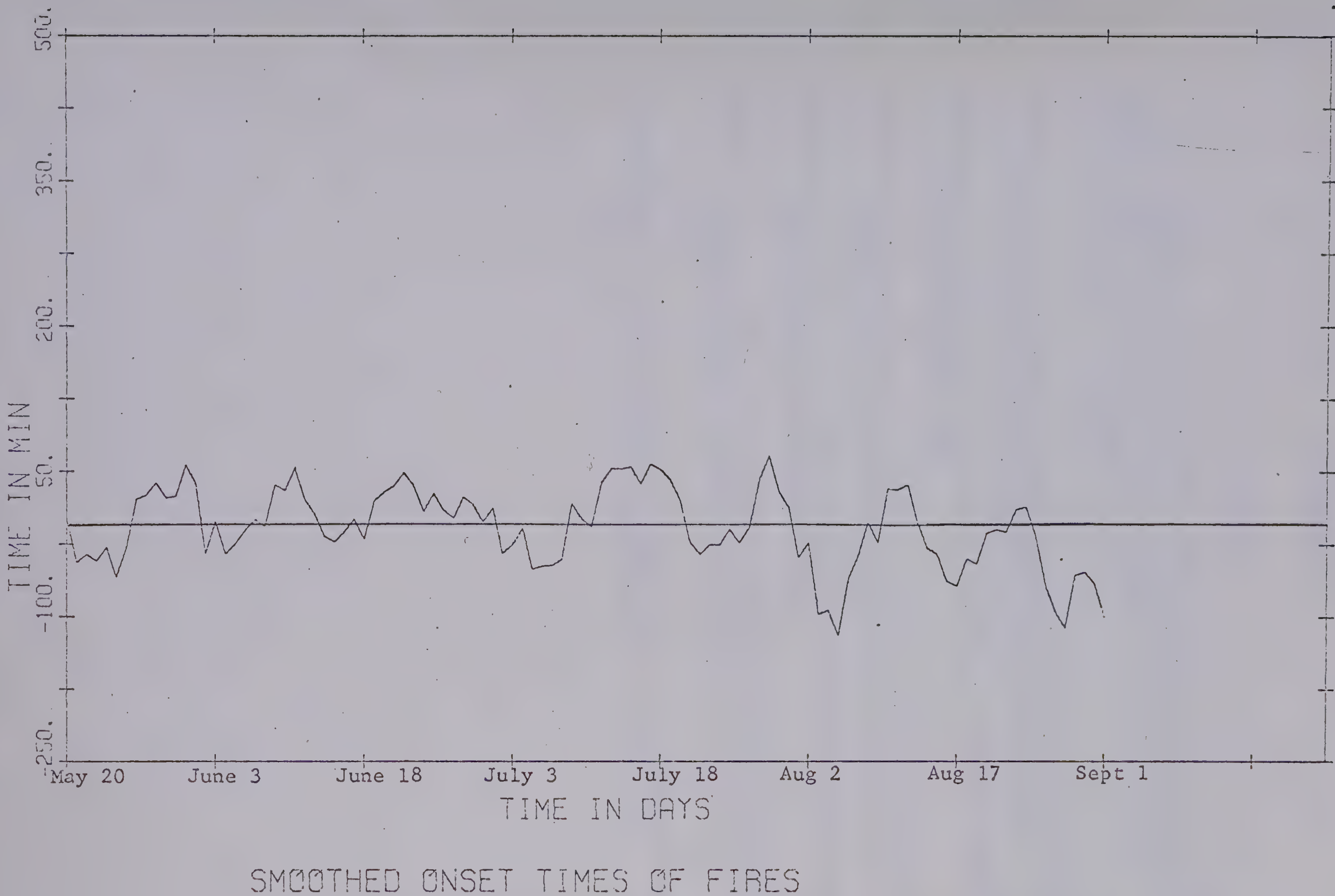


Figure A.2 VARIATIONS IN THE SMOOTHED DISTRIBUTION OF MEAN DAILY ONSET TIMES FROM THE SEASONAL MEAN. The seasonal mean shown by the horizontal line is 1512 MST. The plot commences on May 20 and concludes on September 1.

APPENDIX B

GLOSSARY

Certain terms used in this presentation are not commonly encountered in the field of meteorology. For the benefit of the reader unfamiliar with the meanings of this terminology, the following list of definitions has been constructed.

build-up index = an index designed to measure the aridity of the fuels and give some indication regarding their combustibility.

crown fire = a fire that advances from top-to-top of trees independently of the surface fire.

dielectric constant = the property of a material that determines the maximum amount of electrostatic energy that can be stored.

ground fire = a fire that consumes the organic material beneath the surface litter on the forest floor.

spread index = an index which combines the wind-speed and the fuel's moisture content to provide a measure of the fire's rate of spread.

surface fire = a fire that burns surface litter, loose debris of the forest floor and small vegetation.

APPENDIX C

Graphs showing the relative and cumulative frequencies of thunderstorm occurrence were constructed using the data provided in the Hourly Data Summaries. Figure C.1 shows the curves which were obtained for Grande Prairie and Cold Lake. The curve for Grande Prairie shows a broad maximum occurring at 1900 MST with thunderstorm activity gradually decreasing through the evening. The curve of relative frequencies at Cold Lake shows a bimodal distribution with one maximum occurring between 1700 and 1800 MST and a second maximum occurring between 0100 and 0200 MST. The early-morning maximum was responsible for the early mean times of thunderstorm occurrence found in the eastern part of the province in Figure 4.1. Figure C.1 provides evidence that a large proportion of the thunderstorms occurring in the eastern part of the province are nocturnal thunderstorms.

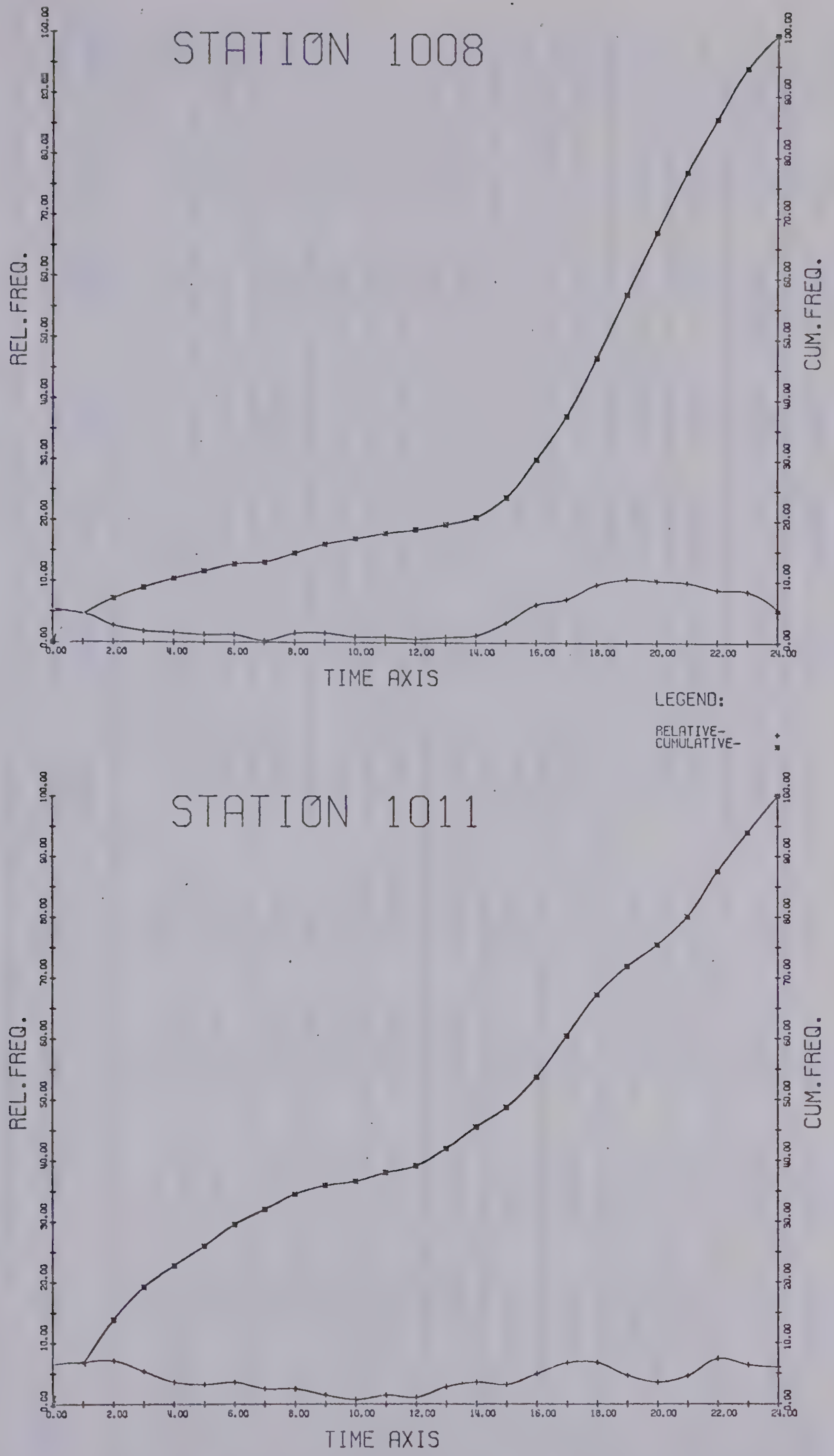


Figure C.1 CURVES OF RELATIVE AND CUMULATIVE HOURLY FREQUENCIES OF THUNDERSTORM OCCURRENCE FOR GRANDE PRAIRIE (1008) AND COLD LAKE (1011).

APPENDIX D

TABLE D.1

CORRELATION COEFFICIENTS FOR ELEVATED FORESTS (36 STATIONS)

	ELV.	LAT.	LONG.	DRY	WET	DRY-WET	MEDIAN DATE	STM. DUR.	STK./STM.	DISCH. RATE	INT. BEAR.	ONSET TIME
1	1.00	--	--	0.12	-0.00	-0.07	0.40	-0.27	-0.21	0.34	0.37	0.15
2	--	1.00	--	-0.19	-0.10	0.01	-0.11	0.27	0.23	0.01	0.12	-0.04
3	--	--	1.00	-0.16	0.00	0.10	0.13	0.06	-0.13	0.23	0.14	0.04
4	0.12	-0.19	-0.16	1.00	-0.19	-0.12	0.01	-0.06	-0.01	-0.06	0.20	0.33
5	-0.00	-0.10	0.00	-0.19	1.00	-0.59	-0.00	-0.21	-0.29	-0.07	-0.24	--
6	-0.07	0,01	0.10	-0.12	-0.59	1.00	-0.08	0.30	0.41	0.20	0.29	-0.12
7	0.40	-0.11	0.13	0.01	-0.00	-0.08	1.00	0.18	0.13	0.28	-0.39	0.26
8	-0.27	0.27	0.06	-0.06	-0.21	0.30	0.18	1.00	0.39	-0.04	0.37	-0.05
9	-0.21	0.23	-0.13	-0.01	-0.29	0.41	0.13	0.39	1.00	0.52	0.06	0.07
10	0.34	0.01	0.23	-0.06	-0.07	0.20	0.28	-0.04	0.52	1.00	-0.30	0.29
11	-0.37	0.12	0.14	0.20	-0.24	0.29	-0.39	0.37	0.06	-0.30	1.00	-0.17
12	0.15	-0.04	0.04	0.33	--	-0.12	0.26	-0.05	0.07	0.29	-0.17	1.00

TABLE D.2

t- SCORES FOR ELEVATED FORESTS (36 STATIONS)

	ELV.	LAT.	LONG.	DRY	WET	DRY-WET	MEDIAN DATE	STM. DUR.	STK./STM.	DISCH. RATE	INT. BEAR.	ONSET TIME
1	0.0	--	--	0.73	0.02	0.43	2.73	1.69	1.29	2.27	2.45	0.87
2	--	0.0	--	1.18	0.61	0.05	0.67	1.66	1.38	0.07	0.69	0.26
3	--	--	0.0	0.97	0.02	0.57	0.36	0.35	0.78	1.42	0.84	0.24
4	0.73	1.18	0.97	0.0	1.15	0.70	0.03	0.34	0.07	0.32	1.20	2.14
5	0.02	0.61	0.02	1.15	0.0	5.30	0.0	1.30	1.84	0.47	1.52	--
6	0.43	0.05	0.57	0.70	5.30	0.0	0.47	1.90	2.87	1.20	1.87	0.74
7	2.73	0.67	0.36	0.03	0.0	0.47	0.0	1.06	0.75	1.80	2.64	1.64
8	1.70	1.66	0.35	0.34	1.30	1.90	1.06	0.0	2.70	0.23	2.46	0.31
9	1.29	1.38	0.78	0.07	1.84	2.87	0.75	2.70	0.0	4.14	0.35	0.39
10	2.27	0.07	1.42	0.32	0.41	1.20	1.80	0.23	4.14	0.0	1.95	1.86
11	2.45	0.69	0.84	1.20	1.52	1.87	2.64	2.46	0.35	1.95	0.0	0.99
12	0.87	0.26	0.24	2.14	--	0.74	1.64	0.31	0.39	1.86	0.99	0.0

TABLE D.3

CORRELATION COEFFICIENTS FOR LOWLAND FORESTS (43 STATIONS)

	ELV.	LAT.	LONG.	DRY	WET	DRY-WET	MEDIAN DATE	STM. DUR.	STK. STM.	DISCH. RATE	INT. BEAR.	ONSET TIME
1	1.00	--	--	0.03	0.30	-0.27	0.41	-0.07	-0.41	-0.00	-0.28	0.05
2	--	1.00	--	0.19	-0.36	0.36	-0.60	0.36	0.10	-0.26	-0.09	-0.02
3	--	--	1.00	0.09	0.13	0.11	0.01	-0.14	-0.66	-0.39	-0.29	0.32
4	0.03	0.19	0.09	1.00	-0.37	0.30	-0.11	0.12	0.07	0.08	0.16	0.04
5	0.30	-0.36	0.13	-0.37	1.00	-0.62	-0.25	-0.25	-0.25	0.06	0.21	--
6	-0.27	0.36	0.11	0.30	-0.62	1.00	-0.41	0.46	0.19	0.01	0.06	-0.17
7	0.41	-0.60	0.01	-0.11	-0.25	-0.41	1.00	-0.15	-0.01	0.05	-0.15	-0.01
8	-0.07	0.36	-0.14	0.12	-0.25	0.46	-0.15	1.00	0.12	-0.13	0.04	-0.42
9	-0.41	0.10	-0.66	0.07	-0.25	0.19	-0.01	0.12	1.00	0.68	0.07	-0.02
10	-0.00	0.26	-0.39	0.08	0.06	0.01	0.05	-0.13	0.68	1.00	0.30	0.06
11	-0.28	-0.09	-0.29	0.16	0.21	0.06	-0.15	0.04	0.07	0.30	1.00	-0.17
12	0.05	-0.02	0.32	0.04	--	-0.17	-0.01	-0.42	-0.02	0.06	-0.17	1.00

TABLE D.4

t- SCORES FOR LOWLAND FORESTS (43 STATIONS)

	ELV.	LAT.	LONG.	DRY	WET	DRY-WET	MEDIAN DATE	STM. DUR.	STK./STM.	DISCH. RATE	INT. BEAR.	ONSET TIME
1	0.0	--	--	0.16	2.04	1.82	3.14	0.46	3.10	0.01	1.90	0.35
2	--	0.0	--	1.26	2.65	2.64	6.08	2.65	0.65	1.80	0.57	0.10
3	--	--	0.0	0.55	0.83	0.69	0.09	0.93	7.59	2.91	2.06	2.25
4	0.16	1.26	0.55	0.0	2.70	2.08	0.71	0.78	0.45	0.52	1.06	0.22
5	2.04	2.65	0.83	2.70	0.0	6.49	1.71	1.68	1.74	0.40	1.40	--
6	1.82	2.64	0.69	2.08	6.49	0.0	3.11	3.72	1.23	0.09	0.41	1.08
7	3.14	6.08	0.09	0.71	1.71	3.11	0.0	0.95	0.05	0.32	0.95	0.03
8	0.46	2.65	6.93	0.78	1.68	3.72	0.95	0.0	0.76	0.82	0.27	3.21
9	3.10	0.65	7.59	0.45	1.74	1.23	0.05	0.76	0.0	7.95	0.43	0.11
10	0.0	1.80	2.91	0.52	0.40	0.09	0.32	0.82	7.95	0.0	2.12	0.37
11	1.90	0.57	2.06	1.06	1.40	0.41	0.95	0.27	0.43	2.12	0.0	1.09
12	0.24	2.25	2.25	0.22	--	1.08	0.03	3.21	0.11	0.37	1.09	0.0

APPENDIX E

Listing of the mean values obtained from the application of the ALR and the AEH techniques.

TABLE E.1

RESULTS FROM THE AEH TECHNIQUE

ASPECT:	E	S	N	W
ONSET TIME (MST)	15:25	15:43	15:54	16:12
STORM DURATION (MIN.)	91.5	87.5	76.4	78.3
MEDIAN DATE OF STORM ACTIVITY	JULY 21	JULY 6	JULY 19	JULY 11
STKS. PER STORM	24.8	24.7	16.6	27.4
DISCHARGE RATES	1.1	1.5	1.1	1.4

TABLE E.2

RESULTS FROM THE ALR TECHNIQUE

ZONE:	I	II	III	IV	V
ONSET TIME (MST)	15:40	15:41	15:18	15:24	15:54
STORM DURATION (MIN.)	88.0	73.5	73.5	78.0	86.2
MEDIAN DATE OF STORM ACTIVITY	JULY 17	JULY 18	JULY 14	JULY 14	JULY 14
STKS. PER STORM	12.2	18.6	19.8	15.2	20.5
DISCHARGE RATES	1.0	1.8	1.7	1.3	1.3
MEAN ANG. OF ATTACK	209.9	193.1	223.4	232.1	238.5

APPENDIX F

TABLE F.1

LISTING OF THE NUMBERS OF THUNDERSTORM REPORTS RECEIVED DAILY OVER THE INTERVAL FROM 1962 TO 1968 INCL.

	A	M	J	J	A	S	O
1	0	14	31	151	232	69	4
2	0	5	88	194	151	82	2
3	0	5	40	189	420	12	4
4	0	0	110	249	255	33	7
5	0	12	119	212	97	8	2
6	0	6	264	162	179	58	0
7	0	22	250	392	73	20	2
8	0	6	108	180	181	16	0
9	0	29	145	225	102	55	0
10	0	17	104	157	187	32	0
11	0	20	207	135	162	23	1
12	0	32	73	177	130	45	1
13	0	39	53	358	74	30	0
14	0	24	90	356	82	4	1
15	0	28	124	377	87	7	0
16	0	41	349	351	119	3	1
17	0	25	263	603	135	3	0
18	0	9	152	355	132	6	3
19	5	12	259	257	70	7	0
20	1	16	164	154	114	0	0
21	1	43	104	204	185	1	0
22	1	41	104	266	143	15	0
23	1	84	197	267	77	11	0
24	10	70	199	142	66	6	0
25	3	122	239	163	54	2	0
26	0	184	170	182	101	2	0
27	0	69	100	319	81	7	0
28	5	76	191	369	47	12	0
29	0	191	114	184	46	10	0
30	24	57	71	286	26	2	0
31	–	76	–	194	35	0	0

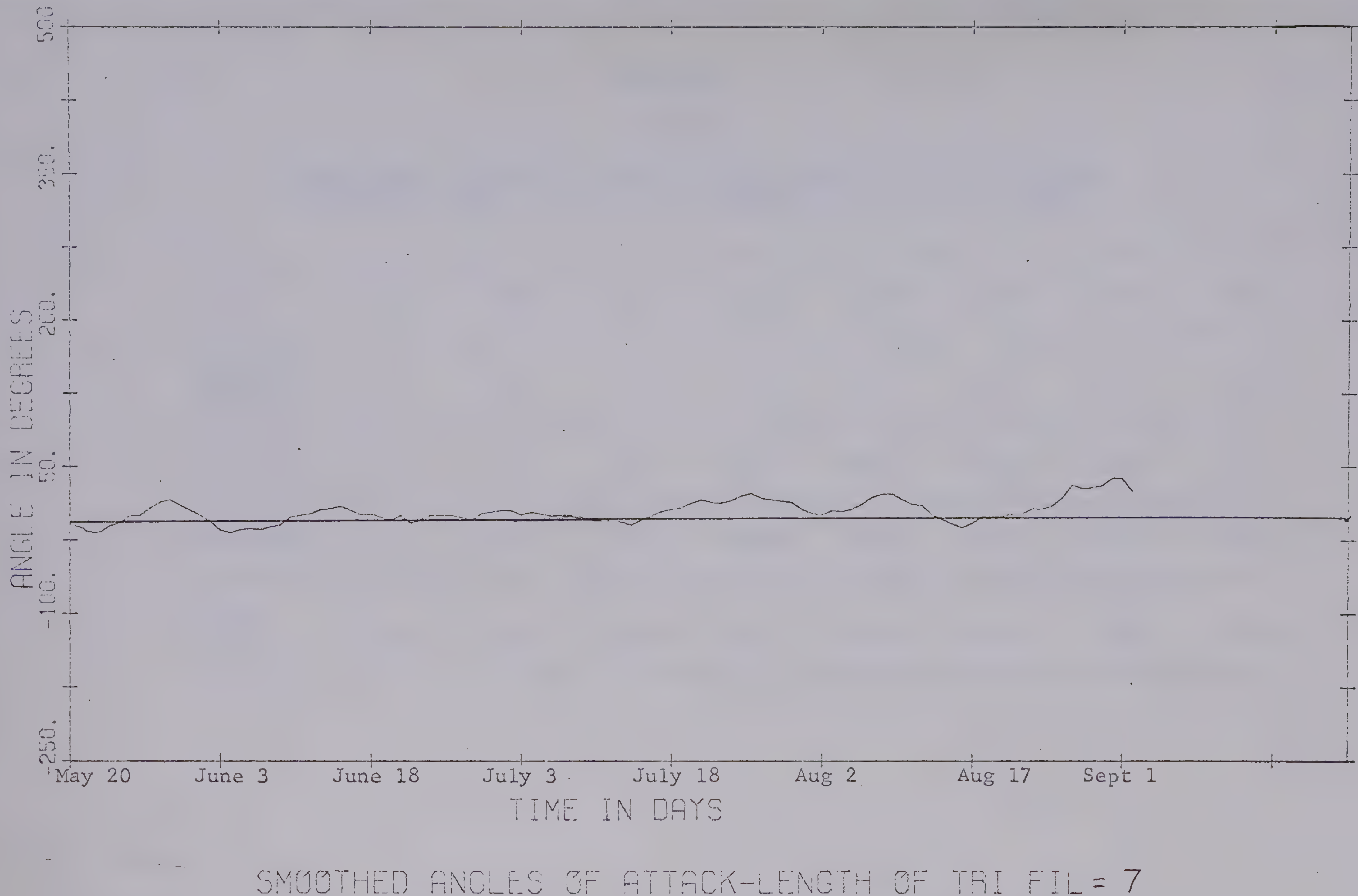


Figure G.1 VARIATIONS IN THE SMOOTHED DAILY INITIAL BEARINGS FROM THE SEASONAL MEAN. The horizontal line represents the seasonal mean of 227.1 degrees. The graph commences on May 20 and continues to September.

APPENDIX H

TABLE H.1

CORRELATIONS BETWEEN THE OCTANT IN WHICH STORMS ARE FIRST OBSERVED AND VARIOUS STATION AND STORM CHARACTERISTICS IN ELEVATED FORESTS.

OCTANT:	N-NE	NE-E	E-SE	SE-S	S-SW	SW-W	W-NW	NW-N
STATION ELEVATION	0.48	0.33	0.39	0.13	-0.21	-0.43	-0.25	0.10
LATITUDE	-0.29	-0.12	-0.09	0.06	0.21	0.18	0.12	-0.24
LONGITUDE	-0.13	-0.18	0.13	-0.09	-0.15	0.10	0.14	0.03
ONSET TIME	0.03	-0.03	-0.00	-0.15	0.23	-0.06	0.13	-0.16

TABLE H.2

CORRELATIONS BETWEEN THE OCTANT IN WHICH STORMS ARE FIRST OBSERVED AND VARIOUS STATION AND STORM CHARACTERISTICS IN LOWLAND FORESTS.

OCTANT:	N-NE	NE-E	E-SE	SE-S	S-SW	SW-W	W-NW	NW-N
STATION ELEVATION	0.16	0.12	0.33	0.05	0.16	-0.19	-0.06	-0.24
LATITUDE	0.01	0.18	-0.07	-0.01	-0.32	0.04	-0.10	0.29
LONGITUDE	0.16	-0.02	0.23	0.00	0.23	-0.39	-0.13	0.06
ONSET TIME	-0.02	-0.32	0.32	-0.04	0.06	-0.09	0.04	-0.04

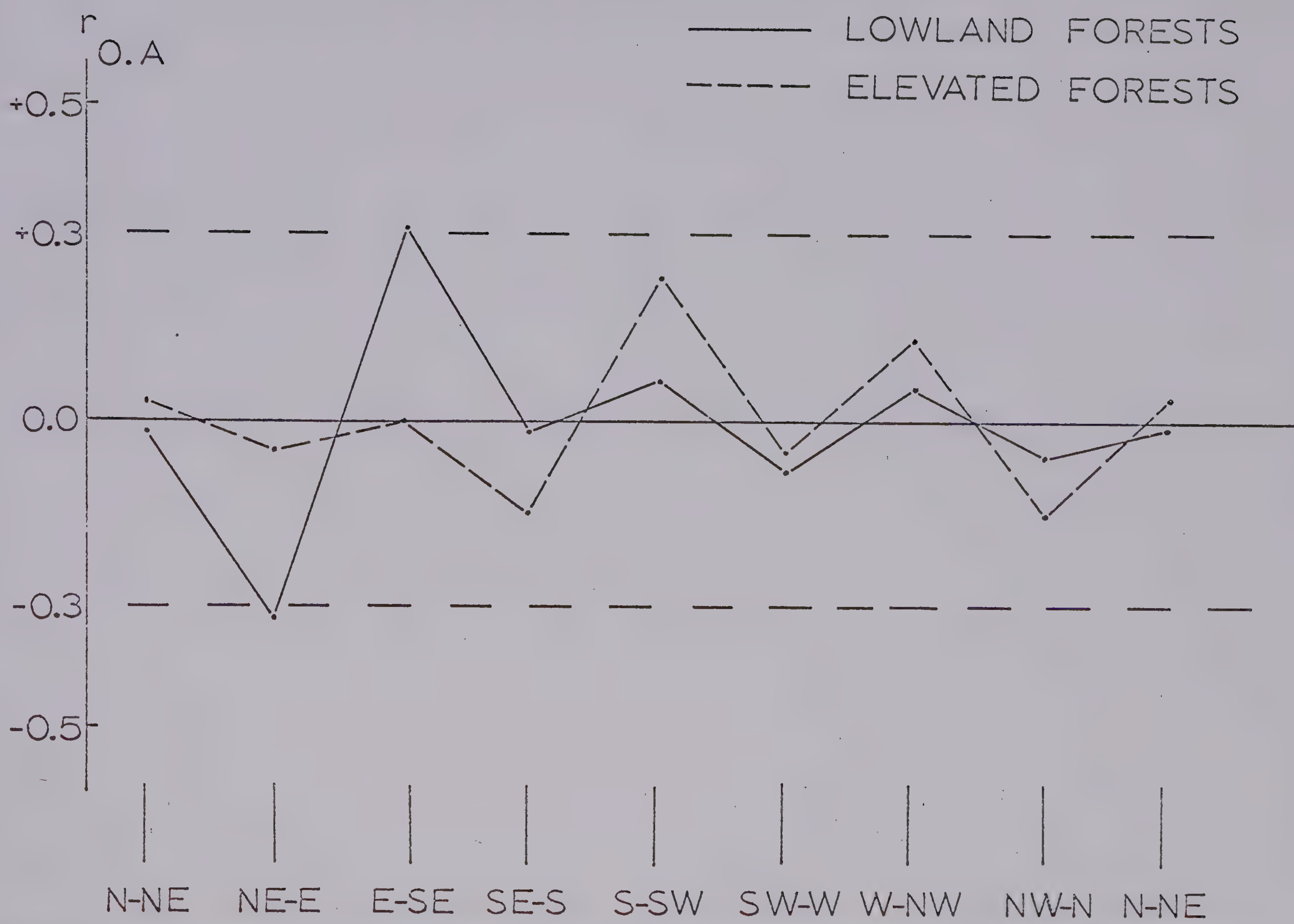


Figure I.1 THE RELATIONSHIPS BETWEEN ONSET TIMES AND THE RELATIVE FREQUENCIES OF STORMS SIGHTED IN A PARTICULAR OCTANT. The correlation coefficients are given along the ordinate.